OUTLINES OF GEOLOGY

JAMES GEIKIE, LL.D., F.R.S.

1896
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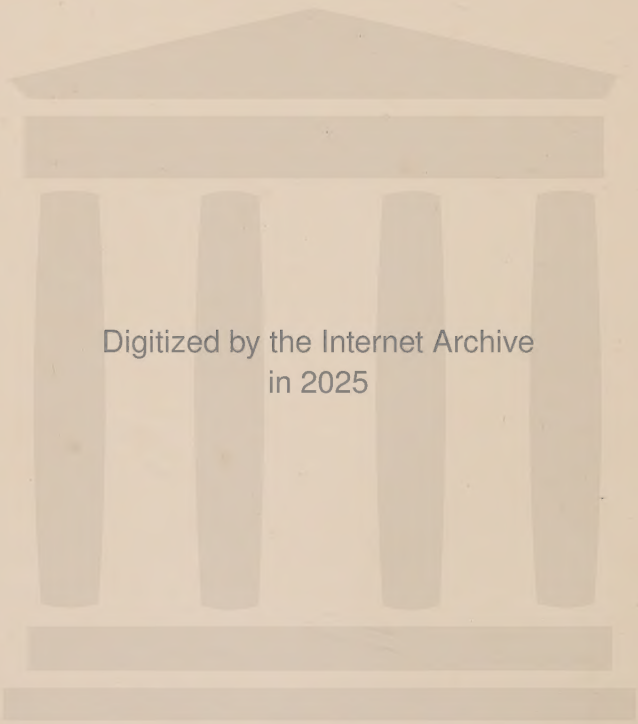

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OUTLINES OF GEOLOGY

AN INTRODUCTION TO THE SCIENCE

FOR

JUNIOR STUDENTS AND GENERAL READERS.

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PREFACE.

HAVING as a teacher felt the want of a moderately sized text-book of Geology, I commenced the preparation of this manual some years ago, but other and more pressing work has delayed its completion until now. In a book intended for junior students, and those readers who desire to obtain only a general view of the scope and bearing of the science, originality need not be expected—at all events it will hardly be met with in these pages. Nor has it been thought necessary to give references to original sources of information, since those who wish to go deeper into the various branches of the subject will doubtless consult the larger English, French, and German text-books, which contain copious references of the kind required. I have confined myself to giving an outline of the leading phenomena with which geologists have to deal, and these have not been discussed with equal fulness or brevity. Knowing what parts of my subject the beginner finds it hardest to understand, I have treated these in greater detail than I have thought it necessary to do with such portions as are more readily comprehended. Difficult questions, such as those relating to the condition of the earth's interior, about which opinions are likely to differ for years to come, are merely touched upon. They cannot, indeed, be adequately discussed in any general text-book of the science, and it is not until the student has got beyond his manual, and commenced investigation on his own account that the more speculative branches of geology can be profitably considered by him. I may also

state here that I have taken for granted on the part of my readers an elementary knowledge of Physical Geography. That science is now so generally taught in schools that it seemed needless to burden my pages with a bald statement of facts which every moderately educated youth already knows. The space thus saved has enabled me to devote more attention to the subject of Physical Geology than could otherwise have been given within the limits I had set for myself. Historical Geology has necessarily been treated in a sketchy manner; all that I have attempted being to give the reader a kind of bird's-eye view of the fields already traversed by the many busy devotees of the science.

Of course the mere reading of a text-book will never make one a geologist. The most such a book can do is to aid and direct the student, and to incite him to use his own eyes as an observer of nature. If in this little treatise I have in any measure succeeded in doing so I shall be more than content with the result of my self-imposed task.

The figures of fossils and several other illustrations, which last are distinguished by the letter R, have been borrowed from the well-known *Physical Geology and Geography of Great Britain* by my friend Sir A. C. Ramsay. For the use of these I am under many obligations.

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CHAPTER I.

INTRODUCTORY.

Definition of Geology—The present as an interpreter of the past—Operations of Nature have always been the same in *kind* but not necessarily in *degree*—The two great divisions of geological agencies.

Geology, in its widest sense, is concerned with observations of minerals, rocks, and fossil organic remains, and with the inferences which may be drawn from those observations. Its object is thus not only to note the nature and position of the various materials which constitute the solid crust of our globe, but by processes of inductive and deductive reasoning to ascertain how minerals and rocks have been formed and caused to assume the different appearances which they now present. In few words then, this science might be defined as an inquiry into the history or development of the earth's crust, and of the several floras and faunas which have clothed and peopled its surface. It thus treats of the genesis of oceanic and continental areas—of mutations of climate—of the appearance and disappearance of successive tribes of plants and animals. More than this, in revealing the past it throws strong light upon the present, and has, perhaps more than any of the cognate sciences, tended to revolutionise our conceptions of nature, and to lead zoologists and botanists into fruitful fields of inquiry which their own proper studies, no matter how assiduously cultivated, could never have enabled them to reach.

Dealing, as geology does, with the operations of nature in the past, it is obvious that the student's first aim must be to obtain a clear knowledge of the mode in which nature works at present, before he attempts to interpret the record of the rocks. Without such preliminary knowledge it is just as hopeless to attempt to decipher that record as it would be to endeavour to understand a page of Greek without having first mastered the grammar and rudiments of that language. Attention must be directed then, at the outset, to a study of those great forces by the action of which

the crust of our globe is being continually modified. It is essential that we learn to appreciate the work done by the atmosphere, by frost and snow and ice, by rain and underground water, by rivers and lakes, by the sea, by plants and animals, and by the subterranean forces, before we can expect to recognise the different parts which those various agents of change have performed in the past.

We take the first step in geological knowledge when we recognise the fact, as who does not, that the solid lands upon which we live are undergoing certain modifications by natural operations. We note how rocks in many places are breaking up under the action of the weather and crumbling down into grit and sand; how rivers are gradually undermining their banks; how the waves and breakers of the sea are eating into the land and causing shore-lines to recede; or we observe how rivers are accumulating materials in their lower reaches and silting up the sea at their mouths; how in some places owing to tidal action certain shallow bays are being gradually filled up, and the coast-lines seem to be advancing. Or, again, we hear of the terrible destruction brought about by landslips, and by avalanches; and we see in certain mountain-regions how those wonderful ice-rivers or glaciers carry slowly down their valleys immense piles of rock-rubbish which have fallen from the crags and precipices above them. We know, also, how some fair lands have been shaken by terrible earthquakes, and their configuration greatly changed—crags and cliffs hurled downwards, and rivers forced to find for themselves new channels—wide tracts formerly portions of the sea-bed now raised above the highest tide-mark, or, as the case may be, extensive areas of dry land now permanently submerged. Ever and anon, too, we are startled by the news of some volcanic mountain in eruption, during which dust and showers of stones are scattered far and wide, and vast sheets of molten matter or inundations of mud desolate the surrounding regions. Few of us have not also realised the fact that certain changes are being brought about by the action of plants and animals. The conversion of shallow sheets of water into marsh and bog and meadowland by the growth of vegetation; the formation of coral reefs and coral islands in the great Pacific Ocean are facts familiar to all.

Now, if we have just grounds for a belief in the constancy of nature we must infer that the modifications which have affected the earth's crust in the ages that have passed must have been the same in kind as those which are taking place in the world around us. The circulation of the atmosphere and the waters—the reaction of the internal heat of the earth upon the earth's crust—and the work

of plants and animals must have produced in the past the same kind of changes as they are bringing about in the present. The more vividly, therefore, we can picture to ourselves the operations of nature in our own day, the more clearly we grasp her plan, and follow her method of work ; and the more earnestly we strive to bring this realisation of the present to illuminate the past, the better observers and discoverers we shall become.

Although we cannot but believe it to be true that the work done by geological agents of change has always been the same in kind, it does not follow that this work has always been accomplished on the same scale and at the same rate as at present. The operations of nature have been the same *in kind*, but not necessarily *in degree*. As we advance in our inquiries we shall find good reason to conclude that certain changes have taken place on a much more extensive scale at certain periods of the past than similar changes are being effected in our day. But this by no means weakens the principle upon which the science of geology is founded, viz. that the Past is to be interpreted through the Present. Such being the case, our first endeavour must be to obtain a knowledge of the action of the geological agents in our own time. To simplify study it becomes necessary to classify those agents, and, so far as possible, to consider each by itself. But, as there are no hard and fast lines in nature, it is obvious that any classification we adopt must be more or less arbitrary. "Nothing in the world is single," and we shall find that the various agents of change are so intimately associated in their work that it is often very hard or even impossible to consider one without constant reference to various others. Nevertheless some kind of classification is necessary, and geologists generally are agreed in arranging the work performed by the various geological agents under two great divisions, viz.—I. **Superficial** or **Epigene Action**, and II. **Subterranean, Plutonic**, or **Hypogene Action**. Under the first of these we treat of the action of the **Atmosphere**, of **Water**, and of **Plants** and **Animals** : while under the second we consider that of the **Subterranean forces**.

CHAPTER II.

GEOLOGICAL ACTION OF THE ATMOSPHERE.

Wind—Destructive action of—Reproductive action of—Sand-dunes, formation of—Distribution and mode of occurrence of—Source of materials of—Dust showers—Blood rain—Preternatural rains—Fulminary Tubes or Fulgurites.

THE operations considered under the head of **Superficial, Surface, or Epigene Action** embrace all those which affect chiefly the superficial portions of the earth's crust. There is a certain advantage, therefore, in beginning our studies with a review of the phenomena which are most familiar to us. Moreover, as we shall afterwards learn, it is through the action of the superficial agents of change that most of the rock-masses which enter into the framework of our lands have been formed. The first of those agents with which we have to deal is the Atmosphere. As is the case with other geological workers, the effect of its action is twofold—*destructive* and *reproductive*.

WIND.

1. Destructive action.—In most countries wind, as a geological agent, acts chiefly in association with water. Thus it intensifies the action of the sea by raising great waves and billows which powerfully assail the rocks along a coast-line. In like manner it produces waves in lakes and drives the waters upon the shore, which thus act with greater energy than they could otherwise do. Nor can the geologist omit to take note of the destructive action of wind during storms. In certain mountain-regions a cold wind blows down the valleys in the evenings succeeding calm and warm days. In the Cordillera so strong sometimes is this mountain-wind that stones are sent flying along the ground; and the frequent repetition of this action must result in no inconsiderable removal of material down the valleys. It is not needful to do more than refer in a word to the sudden ruin which accompanies the passage of a

hurricane across a country—the overturning of trees, the destruction of life, and the sweeping of the wreckage of the land into river or sea, are significant to the geologist. There are some parts of the world which are peculiarly subject to great storms, and it cannot be doubted that under somewhat different arrangements of sea and land, such as we know have obtained in past geological times, similar severe storms may have periodically disturbed other regions of the globe which are now seldom visited in that way.

But it is in countries which are rainless, or have only a very inconsiderable rainfall, that the action of the wind as a powerful agent of change is most remarkably displayed. In such regions, chiefly confined as they are to the lower latitudes, the diurnal range of temperature is often excessive. Exposed to the fierce rays of the noontide sun the rocks expand, and again rapidly contract when the air is cooled by radiation at night. This alternate expansion and contraction sometimes results in actually splitting stones, and as Dr. Livingstone observed in Central Africa, sharp angular fragments are thrown off from the rocks, varying from a few ounces to one or two hundred pounds in weight. Where this action is less pronounced it nevertheless tends to disintegrate rock-surfaces, which in time are crumbled down into grit and sand and dust. Even in countries where no such great diurnal range of temperature occurs, similar changes must be going on. Expansion and contraction of rocks doubtless takes place in our own country, and must aid to some extent in the process of disintegration. But any such action is here obscured by the much more obvious and effective working of frost, rain, and other subaërial agents. In rainless, or all but rainless regions, however, such as the great basin of the Western Territories of the United States, the results of the action referred to are very remarkable. If the air in such regions were motionless, or nearly so, we might conceive of a time arriving when the crumbling rocks would eventually be buried under their own ruins, and thus come to be protected from the effect of changes of temperature. But the winds prevent this by removing the grit and sand and thus leaving new surfaces to be acted upon. The grit and sand thus carried away become potent agents of destruction. They are driven by the wind against the rocks as a veritable "sand-blast," and the rocks become ere long roughened and channelled or rubbed and smoothed unequally, according as they yield more or less readily to the battering of the grit and sand which are borne against them In this manner cliffs become undermined, and the rock-masses giving way, fall to the ground, where they are in like manner attacked, and, becoming worn away most rapidly towards the base, eventually assume the appearance of irregular blocks supported upon

pedestals. The pedestals, continuously rubbed and filed, by and by yield, and the blocks above are overturned, to be again worn by the sand-blast and gradually chiselled into tabular forms of smaller size. So the action proceeds until eventually whole masses become disintegrated and their materials travel onwards with the wind.

This destructive action results in the gradual lowering of the land-level and in the production of sandy wastes. Should such wastes be intersected by rivers flowing from some distant mountain-region it is evident that much sand, blown into the water-courses, may be carried away, while the finer and lighter dust may be transported by the wind into distant countries where no such wind-erosion is going on. Thus the level of the latter may be raised at the expense of that region which is being converted into a sandy desert.

2. Reproductive Action—Dunes.—The sand produced by disintegration of rocks, and carried forward by the wind, is usually heaped up in the form of *Dunes*—that is, hills or hillocks and ridges. These sand-hills or dunes are generally arranged in more or less parallel lines at right angles to the direction of prevalent winds. But as might have been expected this parallelism is not always maintained. Sometimes the sand-hills form tumultuous accumulations, due, doubtless, to local eddies or irregularities in the direction and force of the winds.

The sand swept along the surface of the land is arrested in its progress sometimes by a hollow, sometimes by some inequality, as a bush or tuft of grass, a stone or projecting rock-mass or ridge. In the case of a hollow the march of the sand is interrupted until the hollow is filled up and obliterated, after which it continues on its way. Such a hollow, therefore, does not necessarily give rise to any irregularity of the surface, it is simply smoothed over and disappears. But in the case of any object projecting above the surface over which the sand is advancing an irregularity is the inevitable result (see fig. 1). The sand accumulates in front of the projection,

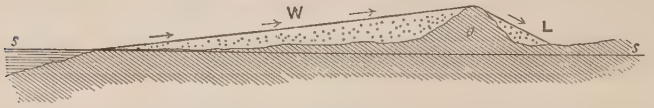


Fig. 1.—formation of sand-dunes.
o, Obstacle intercepting sand; W, windward side; L, lee side; *s s*, sea-level.

forming a gently-sloping bank, which gradually rises in elevation until the grains top the obstacle and fall over on the lee side, where they by and by form a short and steeply-sloping talus. A little hillock formed in this way may eventually grow into a large dune. But the dominant point of the ridge in that case will not

overlie the site of the obstacle which gave rise to the original inequality. For as the sand travels forward the ridge must necessarily advance in the direction of the wind. Any surface, then, over which loose sand begins to travel will, owing to its irregularities, give rise to more or less numerous ridges of sand. As the sand continues to increase in quantity the hollows between successive little ridges will tend to fill up, and gradually these ridges will be replaced by a series of banks and mounds.

The sand of dunes naturally varies in character with that of the rocks from which it has been derived, but it is generally siliceous. The size of the grains varies from finest dust up to coarse grit. A section of a dune often shows layers of fine sand alternating with coarser gritty material. In maritime sand-hills we may sometimes see quantities of shell-débris, fragments of drift-wood, seaweed, etc., and now and again a few stones. It has been observed that the quartz-grains in the blowing sands of deserts are often more rounded than the sand which is carried forward in a stream. This is due to the fact that in the case of wind-driven sand the particles suffer proportionately more attrition. They are rolled along the ground and over each other, while in a river much of the sand is carried in suspension.

Dunes composed of homogeneous materials, and in which the grains do not differ materially in size or colour, seldom show any trace of internal structure. But when the constituent materials vary in character and size, as is often the case in maritime regions, they frequently exhibit traces of the mode in which they have been heaped up. Lines and layers of bedding become conspicuous, and these lines and layers correspond generally to the slopes of the dune, although they are often confused, and present the appearance called *false bedding* or *diagonal bedding*. Occasionally a line or layer of vegetation may make its appearance, marking a former surface upon which plants grew.

Dunes may occur upon sandy coasts, or in any regions where arenaceous accumulations are exposed to the action of the wind. Thus they are well developed here and there upon the coasts of our own islands, as along the shores of the Moray Firth, on the coasts of Aberdeenshire, Forfarshire, Fifeshire, especially between the Firth of Tay and St. Andrews Bay, where in Tents Moor the characteristic parallel arrangement is very well developed ; and again, on the coasts of East Lothian, Ayrshire, and many of the islands of the Outer and Inner Hebrides. In England sand-hills are also well seen, as on the shores of Norfolk, where they are 50 or 60 feet in height. They are also conspicuous here and there on the Irish coast, especially on the south coast of Wexford. The

sand-dunes on the shores of the Bay of Biscay have long been noted, and are said to advance inland at the rate of 60 or 70 feet per annum. On the west coast of Australia sand-hills, which reach heights of 200 or 300 feet, extend inland for some ten miles. Along the shores of many inland lakes dunes also make their appearance, as upon the shores of Lake Michigan, where they range in height from 100 to 200 feet. Nor are sand-hills restricted to the shorelands of lakes and oceans. In the dessicated regions of Central Asia, and in other dry desert parts of the earth's surface, such as the Sahara in Northern Africa, and the great basin of Utah and the Colorado, dunes are more or less well developed.

In maritime districts the sand of the dunes is evidently derived from the materials which are spread out by the waves upon the beach. Dried by the sun the portable sand is ready to be carried inland by the wind until it becomes fixed by vegetation. As we shall afterwards see, it has not always been derived from the disintegration of the rocks along the present coast-lines by the waves and breakers, but in many cases is the sifted and re-arranged material formed by the action of extinct glaciers and glacial rivers, etc. It is evident, for example, that the dunes distributed along the western shores of many of the Outer Hebrides have not been derived from the marine erosion of the hard crystalline rocks of those islands, but consist for the most part of the sediment of an older period, which the tides are constantly sweeping inwards from the bed of the sea. So in like manner the shifting sand-hills of Olkucz, Schiewier, and Ozenstockau in Poland, have not been produced by recent subaërial disintegration of rock-masses, but are simply the re-arranged sands which were formed by the action of ice and water during a preceding period. Nor have we any reason to doubt that some of the wide desert regions of the globe are only dessicated sea-beds—such, for example, is the desert of Sahara, which is proved to have been in large part covered by the waters of the sea within a recent period, by the occurrence of shells of the common cockle scattered over its surface up to heights of 900 feet or so above the present sea-level. It is evident that we cannot attribute all the blowing sands in such an area exclusively to subaërial disintegration and the action of the wind.

Dust Showers, Blood Rain, so-called "Preternatural Rains." —In sandy deserts and parched plains the phenomena known as "pillars of sand" or "sand-spouts" are of frequent occurrence, more especially in calm and sultry weather. The pillars owe their origin to the action of whirlwinds, which are caused by the rapid ascent of the air over superheated areas and the consequent indraught that takes place all round. This being irregular gives

rise to the gyratory motion. The dust raised by such whirlwinds forms columns or pillars, which are not infrequently 15 to 20 feet in diameter. They advance in the direction of the prevalent winds, and dust so raised is often carried to a great height, and may be subsequently swept to vast distances by upper currents of the atmosphere. Hurricanes in tropical countries likewise sweep up immense quantities of dust from parched savannah, or plain, or desiccated river-bed, and this dust may in like manner be carried many hundreds of miles before it comes down again. Thus showers of dust from the Sahara often darken the sky at Madeira, and the same dust has been recognised in the south of France and the north of Italy. According to Baron Richthofen a yellowish calcareous loam or clay called *Löss*, which varies in thickness from 50 feet or so up to as much as 1500 feet or more, and which covers vast regions in China, is an accumulation of dust formed in the course of long ages by the action of the wind. But this view has not been accepted by geologists without modification.[1]

Rain falling through clouds of red desert dust will take up some of the dust, and, doubtless, such has often been the origin of the so-called "blood rain"—the cause of so much superstitious terror in olden times.[2]

The fine dust shot upwards during volcanic eruptions has sometimes been transported great distances by the wind. Dust from Hecla has fallen in the Faeröe Islands, in Shetland, and in Norway. Dust from Vesuvius has been carried as far as Constantinople; while, more notable still, dust from the volcano of San Salvador (east of Guatemala) has fallen in Jamaica. In this latter case the dust travelled E.N.E., nearly opposite to the direction of the trade-wind, a distance of about 1000 miles. Volcanic dust is very often black, and rain falling through it comes down as "black rain."

The so-called "preternatural rains" have some interest for the geologist. "Blood rain" and "black rain" have just been referred to, and their origin explained. But many other remarkable "showers" are on record. The "yellow rains" or "sulphur rains" seem, on every occasion where they were carefully examined, to have been due simply to the superabundant presence of pollen. At Lund, in the south of Sweden, the pollen of *Pinus sylvestris* (Scots fir), fell in a shower. It had been carried by the wind from a forest some 35 miles distant. A similar "yellow rain" fell in June 1835, during a thunderstorm at Banff, and many similar in-

[1] See further on the origin of *Löss*, chap. xxv.

[2] The "blood rain" that was supposed to have fallen over-night at the Hague in 1670 owed its sanguine colour to the presence of prodigious swarms of small red water-fleas.

stances might be given. We read also of "manna rains," "falls of grain," etc. Thus a "rain of wheat" fell near Bristol; but the "wheat" proved to be the seeds or kernels of ivy berries which the wind had carried from the ivy-covered houses and trees of the neighbourhood. A fall of real wheat, however, took place in 1804 in Andalusia. The wheat is said to have been "carried by a hurricane across the Straits of Gibraltar from a threshing-floor at Tetuan." The "manna rains" resolve themselves into portions of esculent lichen, which the wind has torn from the leaves of trees and borne to a distance. Such it would seem is the origin of the "manna" which has fallen from time to time in Persia, as at Oroomiah during a famine in 1829, and again at Herat while that place was being besieged. Credible witnesses have also testified to the fall of fish, frogs, molluscs, etc. There seems no reason to doubt that some of these actually did take place. Thus many thousands of herrings, from one and a half to three inches in length, fell near Edinburgh in 1817. A similar shower is recorded to have taken place near Loch Leven in Kinross-shire about 1825. Herring have also fallen in Ross-shire (in 1828), about three miles from Dingwall Firth; and again (in 1830) in the island of Ulva, Argyleshire. It is noteworthy that in most of these cases the fish are said to have been perfectly fresh, many being not quite dead, but sprawling on the ground. It is needless to cite instances of the fall of fish in other countries during tempestuous weather. But reference may be made to the shower of "mussels" (*Bulimus truncatus*), which fell at Montpellier in 1835, as showing further the effect of strong winds. Mention is also frequently made of "falls of frogs," but it seems doubtful whether these have been carried by the wind as the herrings and mussels undoubtedly were. Such "falls," which are said to be of frequent occurrence in Italy, are never witnessed except near the walls of houses; and the inference is that the frogs and toads have simply been washed from the roofs and gutters by the rain. The significance to the geologist of some of those so-called "preternatural rains" is apparent. We see how, as in the case of "showers of herrings," a number of marine organisms may become entombed in the sediment of lakes and rivers, side by side with the remains of fresh-water fish, molluscs, and the débris of terrestrial plants. In temperate regions, which are but seldom visited by hurricanes, such cases must be very exceptional; but in tropical regions, where violent winds are of more or less frequent occurrence, relics of marine life may often be carried inland and dropped into rivers and lakes, just as many relics of terrestrial life are from time to time blown out to sea.

In the diffusion of life over the globe winds have played an important part. In dust showers minute diatoms are often present, and these may sometimes find suitable conditions for themselves in regions very far removed from the place whence they were carried. Seeds also may be transported for enormous distances, and oceanic islands probably owe their covering of vegetation in some measure to the agency of the winds; nor can it be well doubted that the insects and birds of those isolated spots of land have often been introduced in the same way.

Fulminary tubes or Fulgurites.—Some notice of certain effects produced by lightning may be taken here—more, however, on account of their peculiarity than their importance from a geological point of view. These are the so-called *Fulgurites* or vitrified tubes, which are believed to have been formed by lightning. They appear to have been most frequently observed in sand-hills. Thus at Drigg, in Cumberland, a number of such vitrified tubes were seen, and one of them was traced to a depth of not less than 30 feet. The internal surface of the tubes was completely vitrified, glossy, and smooth—the thickness of the wall varying from $\frac{1}{30}$th to $\frac{1}{10}$th of an inch. The tubes were generally compressed, as if from the sinking in of the surrounding loose sand, while the tube was still softened from the effect of heat. In circumference they varied from two up to four inches. Mr. Darwin has described a group of lightning tubes which he saw in some sand-hillocks near Moldanado, at the mouth of La Plata. At that place the sand-hills, not being protected by vegetation, are constantly changing, so that the fulgurites projected above the surface, and numerous fragments were lying near. Humboldt has noticed the effect of lightning on a volcanic peak (15,000 feet high) in Mexico, and similar observations have been made on mountain-tops in other countries, as for example, in the Pyrenees, particularly on the Pic Posets, where the rocks attacked by lightning are said to be covered with a black scoriaceous plaster, which looks as if it had "run" or dripped. The mountain called Little Arrarat seems to be especially rich in fulgurites. The summit, composed of a reddish white trachyte (a volcanic rock), is completely riddled with them, the holes drilled by the lightning being lined internally with a blackish green glass. Similar fulgurites have been described by Mr. Diller as occurring on Mt. Thielson in Oregon. Mr. Rutley has also recently described specimens of the same nature from the Dom du Gouté (Mont Blanc).

CHAPTER III.

GEOLOGICAL ACTION OF TERRESTRIAL WATERS.

Rain, chemical action of—Weathering of rocks—Rain, mechanical action of—Underground water—Springs—Wells—Chemical action of underground water—Stalactites and stalagmites—Mineral springs—Origin of swallow-holes, sinks, pipes, etc.—Mechanical action of underground water—Origin of underground galleries and caves—Deposits in caves, etc.—Local subsidences, rock-falls, and landslips.

I.—RAIN.

1. **Chemical Action.**—Rain is not pure water, but always contains some proportion of oxygen and carbonic acid, which it has absorbed from the atmosphere. After it falls to the ground it derives additional supplies of carbonic acid from the decaying vegetable and animal matter with which all soils are more or less impregnated. Oxygen, carbonic acid, and decaying organic matter are by far the most potent aids to the chemical action of rain. Near towns, it is true, rain often contains other impurities, more especially sulphuric acid and nitric acid, the presence of which leads to the more or less rapid corrosion of metals, and to the disintegration of stones and mortar; but from a geological point of view this particular action is of little importance.

One of the most common results of the chemical action of rain is the oxidation of minerals that can take up more oxygen.[1] Thus the sulphides of iron (*marcasite*, *pyrite*), which are so generally present in many rocks, are prone to become oxidised. Sometimes they are changed into sulphate of iron, but when other bases are present in the rock, the sulphuric acid may seize on these by preference, and leave the iron of the original sulphide free. The iron then becomes oxidised, and appears as ferric, or usually as hydrous-ferric oxide. As the production of this iron oxide in a granular rock tends to force the grains apart, it is evident that such action must lead to the disintegration of the rock.

[1] Some account of the minerals and rocks mentioned in this chapter will be found in chaps. x. and xii.

The presence of organic matter in rain-water often brings about de-oxidation: that is to say, certain minerals are forced to part with some of their oxygen to the organic matter, which has a great affinity for that element.

Oxidation and de-oxidation usually result in a change of colour. Thus the conversion of ferrous oxide into ferric oxide produces generally a dark reddish or yellow-brown tint. This is the origin of those unsightly rusty, and dark discolourations which so often disfigure gray and white sandstones. Again, it is the reduction of ferric oxide to ferrous oxide which gives rise to the light-coloured spots, patches, and bands which so often characterise red sandstones.

But the most powerful agent of change present in rain-water is carbonic acid gas, which has a strong affinity for many substances that enter into the composition of minerals and rocks. Consequently such common minerals as augite, hornblende, mica, the felspars, etc., which contain, amongst other constituents, potash, soda, lime, magnesia, and iron, are attacked by carbonated water—the carbonic acid uniting with some portion of these bases to form carbonates, which are carried away in solution. Pure calcareous rocks (limestones), and rocks which contain much carbonate of lime, are readily acted upon by acidulated rain-water, which converts the carbonate of lime into the soluble bi-carbonate and carries it away.

The result of the long-continued chemical action of rain is best seen in tropical regions, where the rocks are often decomposed to a depth of many feet or even yards. In Brazil, for example, the thickness of altered rock is said to be as much in some places as a hundred yards. In temperate and north temperate regions such great depths of decomposed rock are rarely or never seen; this, as will be afterwards pointed out, is due chiefly to the fact that those countries have, within a recent geological period, been subjected to the grinding action of glacier-ice, which has scraped away the earthy decomposed crusts that previously existed.

Weathering of Rocks.—The decomposed crusts of rocks are not the result of the chemical action of rain alone. Besides this we have to take into account other subaërial agents, especially *frost*, which, as will be afterwards pointed out, is a potent cause of the disintegration of rocks. As it is not always easy, however, to assign to each agent of change its particular share in the production of decomposed crusts, geologists find it convenient to speak of such crusts as *weathered*, *i.e.* as having been formed by the general action of the subaërial forces, amongst which the chemical action of rain is in this case the most potent. The manner in which rocks yield to weathering is regulated chiefly by their composition and

texture. Thus, highly calcareous rocks are more readily acted upon than rocks which contain little or no calcareous matter—limestones wearing away more rapidly than any other rock of equally great geological importance. Again, amongst rocks which do not readily decay under the chemical action of rain, the more porous kinds do not stand so well as the more compact varieties. For the former retain water much more readily than the latter, and are therefore more continuously subjected to its influence; while frost assists chemical action by forcing the grains of the porous rock asunder, thus preparing the way for the action of the re-agents contained in rain. There is no necessary connection, however, between the relative hardness of rocks and the rate at which these succumb to weathering. Thus a hard compact limestone weathers more rapidly than a soft argillaceous or siliceous rock. Neither does it necessarily follow that a thick decomposed crust upon a certain rock is indicative of more rapid weathering than a very thin crust in the case of another rock. Pure limestones, for example, dissolve away with little or no crust, while other rocks, such as many igneous rocks, which consist largely of ingredients that are either insoluble or only sparingly soluble in rain-water, weather with thick crusts.[1] The impurity of a limestone may thus be inferred from the thickness of its crust. Some of the more impure varieties weather with a very thick crust, giving rise to the rock called *rotten-stone*, which is composed chiefly of silica, and silicate of alumina with some ferrous oxide. Calcareous sandstones weather much in the same way as impure limestones—the carbonate of lime is dissolved out, and a honeycombed cavernous mass, or a mere heap of sand and grit, is left behind. Even the purest limestone is rarely without its crust—this being in most cases stained yellow with hydrous ferric oxide.

Crystalline igneous rocks vary indefinitely in the manner of their weathering. Sometimes the weathered crust is a mere pellicle or skin, generally light in colour—white, grey, pale yellow, or pale brown. At other times the crust may be many inches or feet in thickness and much darker in colour. Exceptionally, some entire rock-masses have become decomposed into a kind of rusty brown grit or earth, through which a few scattered balls of hard undecomposed rock may be all that remains to show the original character of the mass. This is particularly the case with some of the coarse-grained basalt-rocks. A very good example is seen in the rock at the cemetery of Balgay Hill, near Dundee. This rock is a coarsely

[1] The "black sands" which occur on the sea-shore in some places, as Bay of Naples, Taranaki, in New Zealand, and elsewhere, are composed of titaniferous iron and magnetite—the insoluble residue of such rocks as basalt.

crystalline diabase which in some places is weathered to a depth of several yards, so that graves are dug in it—the material turned out being a yellowish brown rusty grit or earth, interspersed with balls or cores of the original rock. Nearly all basalt-rocks tend to decompose spheroidally—the rock in typical examples appearing to be built up of large and small spheroids encased in exfoliating crusts. In these rocks the lime contained in the felspar and augite has united with carbonic acid to become carbonate of lime and has been removed in solution, while the general rusty hue is due to the iron of the augite, which has become oxidated and changed into hydrous ferric oxide. Frequently the weathered crusts of the same rocks show dull dirty green discolourations, which are due to the breaking-up and alteration of certain anhydrous minerals (such as augite, olivine, etc.) into hydrous magnesian silicates (such as serpentine, chlorite, etc.)

Gneiss and granite, which are hard crystalline rocks, are sometimes found weathered to a depth of 40 to 150 feet—the weathered rock appearing as a mixture of grit and clay. This clay (kaolin) is the insoluble residue of the felspar, and is used for the finer kinds of pottery.

2. Mechanical Action.—The weathered crusts of rocks tend to be washed down and carried away by the mechanical action of rain, a process which will be fast or slow according to circumstances. From cliffs and steep hill-slopes, the products of decomposition will naturally be removed more rapidly than from exposed rock-surfaces elsewhere. But, fast or slow, all the loose material derived from the weathering of rocks is, under the influence of rain, compelled to travel from higher to lower levels. In this movement the ordinary vegetable soil[1] of course shares. In regions where the rainfall is moderate this onward and downward movement of soil and disintegrated rock-materials is not so strikingly displayed as in countries where the rainfall is great. Yet any one may observe how in the gently-undulating low grounds of our own country rain washes the finer particles down the slopes and spreads them out over the hollows. In the lower reaches of the valley of the Tweed, for example, the undersoil of which consists largely of a tenacious stony clay arranged in a great series of parallel banks or ridges, the long-continued mechanical action of the rain is well shown in the formation of numerous flats of loam and fine clay which occupy the hollows between successive banks of stony clay. The loam and clay are washed down the slopes, while the stones and coarser particles are left behind. This same action is greatly intensified

[1] The formation of soil, which is due to the combined action of many agents, is described later on. See chap. ix.

in some countries, where an extreme diurnal range of temperature gives rise to much rock-disintegration. Heavy rain falling upon the mountains and declivities of such regions rapidly washes down angular stones, grit, and earthy débris to the low grounds. The characters which chiefly distinguish this *rain-wash* are (1) the strictly local nature of the materials, and (2) the angularity of the stones, when these are present.

The mechanical action of rain upon a rock of unequal durability will naturally produce a more or less irregular surface. Those portions which are most readily removed will give rise to hollows, while the harder parts will form prominences. Very few rocks yield so equally as not to show any trace of this action. It is, how-

Fig. 2.—SANDSTONE "WEATHERED" INTO PILLARS. (R.)

ever, more conspicuous in non-crystalline than in crystalline rocks (although many decomposing crystalline igneous rocks show it admirably) and is best seen in such rocks as volcanic tuff, breccia, and agglomerate, or in certain aqueous conglomerates, or better still in accumulations of earth or clay which are charged with stones and boulders (see fig. 3).

II.—UNDERGROUND WATER.

All rocks are more or less porous, and liable to be permeated by water in a greater or less degree. The chemical action of rain is not confined therefore to the mere external skin or crust. We have seen that some kinds of rock become decomposed to great depths to a kind of loose grit and earth. But even where the changes produced by the chemical action of rain are not so obvious—where the rock at a considerable depth from the surface appears firm and unaltered, closer observation will yet often show more or less decided evidence of change. There are very few crystalline rocks (such as granite, gneiss, basalt, etc.) which when examined microscopically do not show traces of decay, even although the specimens selected for examination may have been taken from the deepest portions of our largest quarries. The water which permeates the interstitial pores of rocks has not necessarily soaked through the rock from the surface of the ground. Rocks are invariably traversed by systems of regular or irregular cracks or "joints," as they are technically

Fig. 3.—NATURAL ARCH AND PILLARS, RIO GRANDE. (HAYDEN.)
Effect of "weathering" on a mass of slightly compacted volcanic sand, containing blocks of trachyte (a volcanic rock).

termed, and very frequently they are cut across by vertical or highly inclined fissures of a more pronounced kind, which are called "faults." It is chiefly along bedding-planes and such cracks and fissures that rain-water finds its way downwards, and is enabled to soak through the rock itself at great depths from the surface.

Springs.—The water that travels downwards through the rocks eventually comes to the surface again where it forms *springs*. The course followed by underground water depends upon geological structure; and such being the case we may conveniently class natural springs under three heads: *Dip springs*, *Fissure springs*, and *Junction springs* (fig. 4).

Dip springs occur in regions formed of permeable and practically impermeable strata. The water enters the porous rocks, where these crop out at the surface, and, being unable to penetrate the underlying impermeable rocks, it percolates through the former in the direction of the *dip* or inclination of the strata, until these are truncated, as in a river-valley, when the water issues to the light of

Fig. 4.—DIAGRAM TO ILLUSTRATE ORIGIN OF SPRINGS.
d d, Dip springs; *j j j*, junction springs; *fi fi*, fissure springs.

day *d d*. Dip springs as a rule are shallow, that is to say, the water has come from no great depth, although it may have travelled a long distance underground.

Fissure springs are formed by water percolating downwards and upwards through natural joints and crevices or fissures. Many of these springs are deep-seated. The water, after percolating to great depths, becomes more and more subject to its own pressure, and consequently, when it encounters in its downward course wider fissures opening upwards, it will be forced to ascend by these to the surface *fi fi*. Such springs are typically represented by those which occur in regions of massive crystalline rocks like granite.

Junction springs may occur in rocks of any kind. They are proximately due to interruptions in the underground drainage caused by the abrupt *junction* of the water-bearing rocks with others which may be less permeable. The water, after flowing either through a porous bed or along a series of fissures, suddenly encounters a wall of another kind of rock, and it then rises along the line of junction between this interrupting mass and the water-bearing rocks *j j*. Springs of this kind may either be shallow or deep-seated.

Although springs have been described under these three heads, it must not be supposed that it is always possible to say under which head a particular spring must be classed. It is certain that many springs partake of the characters of all three. That is to say some underground waters may begin their course by flowing through cracks and fissures, and afterwards enter a porous stratum and flow along the line of bedding for great distances until finally, meeting with a sudden interruption in the form of a vertical wall of igneous rock or a fracture and dislocation or other junction, they may be compelled to rise to the surface as junction springs. The accompanying diagram (fig. 4) will serve to illustrate the various origin of natural springs.

Wells.—The rocks of most districts are permeated by water at a certain depth, which may be close to or at a great distance from the surface, according to the geological structure of the ground. This is called the water-level. But, owing to the many changes in the character and distribution of the underlying rocks, it seldom

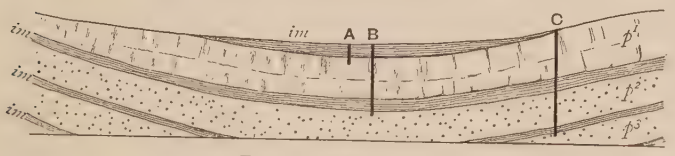


Fig. 5.—ARTESIAN WELLS.
A B C, Wells ; *im*, impermeable strata ; *p*, permeable strata.

happens that the water-level of a district is quite equable throughout, so that the depths of common wells are apt to vary. *Artesian wells* are made possible by the basin-shaped arrangement of porous and impermeable strata. The woodcut (fig. 5) will sufficiently explain their nature. Here we see a succession of permeable (p^1 p^2 p^3) and impermeable strata (im^1 im^2 im^3 im^4). Surface-water enters the permeable strata (p^1 p^2 p^3) and flows down in the direction of the dip or inclination of the rocks until the strata may become surcharged like a sponge, for the water cannot penetrate the overlying and underlying impermeable rocks. It is evident, therefore that were a boring made at A the water in p^1 would rise and gush out as a spring at the surface, in the same manner as the junction springs shown in fig. 5. In like manner borings made at B and C would tap the water in the porous strata p^2 and p^3. Some Artesian wells are sunk to considerable depths. At Grenelle (Paris) the water rises from a depth of 1771 feet ; at Neusalzwerk, near Minden, the depth is 2394 feet ; at Louisville, in Kentucky, 2086 feet ; at St. Louis, on the Missouri, 2624 feet. The hy-

draulic pressure under which the water is forced to the surface is often very great. At Grenelle the fountain ascended at first 112 feet, at Louisville it leapt up 170 feet. It must not be inferred that the strata in which Artesian wells are successfully sunk are all arranged as symmetrically as is shown in the diagram. The continuity of the basin may be very much interrupted, and in many cases Artesian wells merely tap underground waters which would otherwise find an outlet to the surface as junction springs.

The temperature of springs ranges from near the freezing-point up to the boiling-point. There is a spring which issues from the side of the Hangerer, in the Œtzthal at a height of 6742 feet, which is said to be only 1° warmer than ice. In Iceland and other volcanic regions there are boiling springs. Most of the springs in non-volcanic regions which come from moderate depths, being beyond the reach of the summer heat and winter cold, give us the average temperature of the regions in which they occur. Such springs are called *cold springs*. Thus we may conclude that very shallow springs—those which have flowed at no great depth from the surface and for no great distance—will be liable to changes of temperature, being colder in winter and warmer in summer. On the other hand underground water which has come from moderate depths, and which may have flowed for considerable distances, will have the average temperature of the ground; while springs, whether shallow or deep-seated, which have been heated by subterranean influences, will show a higher temperature than that of the locality in which they occur. These latter are called *thermal springs*.

1. Chemical Action.—The chemical action of rain has already been described, and some reference has been made to the action of "interstitial water," *i.e.* the water which soaks through the minute pores and microscopic cracks that occur in all rocks. By the action of this water, and the carbonic acid, oxygen, and other chemical agents which it contains, extensive alterations are often produced in the composition and structure of rocks. Thus certain rocks, such as gypsum, rock-salt, limestone, and dolomite, are attacked and removed in solution. Some dolomitic limestones, formerly well bedded and charged with fossils, have by the action of percolating water lost their carbonate of lime, and the resulting porous rock has subsequently under the same action become a crystalline mass from which all traces of bedding and every vestige of a fossil have vanished. By the removal of mineral matter in solution cavities are formed which may subsequently be filled up again by the introduction of new matter. This change takes place to a greater or less degree in almost all rocks, as will be shown more fully when we come to consider the microscopic structure of

rocks. The composition of fossil organic remains or *petrifactions* shows that these have been subject to similar changes. The organic matter has been either partially or wholly removed, and inorganic matter substituted for it. Thus we have shells, bones, wood, etc., replaced by such minerals as calcite, iron pyrites, quartz, chalcedony, or gypsum. In like manner many natural cracks, fissures, vesicles, etc., in rocks may become filled up in whole or in part by similar mineral substances deposited by infiltrating water. Again there are some rock-forming minerals which are *anhydrous* (*i.e.* they contain no water); these therefore may take up water. Thus ferric oxide may be converted into hydrous ferric oxide, and anhydrous sulphate of lime (*anhydrite*) into the hydrous sulphate (*gypsum*). Another result of the action of interstitial water is the *oxidation* of minerals. This is well seen in the peroxidation of the proto-salts of iron, and in the conversion of sulphides into sulphates. Further, *deoxidation* also may be effected, as in the conversion of ferric oxide into ferrous oxide. Another very important set of changes brought about by percolating water is the breaking-up of minerals composed of silicates of lime, potash, soda, and the oxides of iron and manganese, and the formation of carbonates of these bases, by which the silica becomes free. Many of the minerals acted upon in this manner contain also silicates of alumina and magnesia which are much less readily attacked, but take up water and remain as hydrous silicates. Thus we find that such rock-forming minerals as felspar, augite, and hornblende (which are silicates of alumina, lime, potash, soda, magnesia, and oxides of iron and manganese), have often been broken up, and some of their constituents removed in solution as carbonates, while the free silica is also sometimes carried away in whole or in part,—hydrous silicates remaining behind in the form of clay and kaolin, chlorite, serpentine, steatite, etc.

Stalactites and Stalagmites.—The general action of infiltrating water is well shown in the formation of *stalactites* and *stalagmites*. Carbonated water, while passing through calcareous rocks, dissolves and carries away a portion of the calcium carbonate. When at last the water, thus impregnated with calcareous matter, oozes out on the roof of some underground cavity, it is subject to evaporation, and a thin ring-like pellicle of calcium carbonate is left adhering to the rock by the drops of water as they gather and fall. On the floor of the cavity the water evaporates in the same way, and is thus compelled to give up the calcareous matter which it held in solution. By this constant dropping and evaporating the ring-like pellicles formed on the roof eventually grow, as it were, into long tongue-like and icicle-like pendants, or *stalactites* as they are termed :

while sheets, bosses, and domes (*stalagmites*) at the same time thicken upon the floor, and this to such an extent that they often meet and become continuous with the stalactites, so as to give rise to pillars and columns that seem as if they supported the roof of the cave (fig. 6).

Fig. 6.—SECTION OF CAVE IN LIMESTONE.

a, Entrance; *b*, cave-earth, etc., in bottom of cave; *c d*, stalactites and stalagmites; *f*, blocks fallen from roof; *p*, pipes filled with débris.

MINERAL SPRINGS.—Springs which hold any decided quantity of mineral matter in solution are often called *mineral springs*, or, if we take note of the mineral matter particularly, the springs will be termed *chalybeate*, *siliceous*, *brine*, or *calcareous*, according as their waters contain hydrous ferric oxide, silica, common salt, or carbonate of lime. Chalybeate springs are of common occurrence, especially in countries where ironstone or iron-bearing rocks abound, and they are often met with in bog-covered regions. Siliceous springs are of much less frequent occurrence, and are most commonly met with in volcanic districts. They will be described therefore under the head of volcanic phenomena. Brine or saline springs occur in regions where rock-salt occurs; and calcareous springs appear in like manner in regions of limestone, chalk, and other calcareous strata. Besides these there are many other varieties of mineral springs, such as the so-called *medicinal springs*, and the springs which in Pennsylvania and other districts have yielded copious supplies of oil, derived from the distillation of organic matter contained in the strata. As the substances which are brought to the surface in solution by springs have unquestionably been derived from the rocks through which these waters percolate and flow, it is evident that a very considerable amount of material must in this way be carried up from the bowels of the earth. The result of this transference of matter to the surface is most conspicuous in regions consisting largely of calcareous rocks. Carbonated water percolating along the cracks and fissures of such strata dissolves the rock on

either side, and in this way the joints are gradually widened, and eventually a series of tortuous galleries and chambers are formed. In countries where limestone forms the prevailing rock at the surface this process has often been carried to such an extent that the whole of the rainfall finds its way into subterranean courses, and the entire drainage is conducted underground.

Swallow-Holes, Sinks, Pipes, etc.—The apertures by which the surface-waters enter the underground drainage-system are known as *sinks* and *swallow-holes* in this country, and as *dolinas* in Italy. Their origin is well illustrated by the formation of *pipes* in chalk (fig. 7). In chalk countries the rock is usually covered

Fig. 7.—PIPES IN CHALK.

with an irregular sheet of clay or earthy rubble and flints. These materials represent the insoluble residue of the chalk, the calcareous matter having been dissolved and removed. Here and there the overlying earth and flints appear to lie in somewhat steep-sided troughs or more or less vertical funnel-shaped *pipes*, as they are called. It is evident that such troughs and pipes occupy the position of lines along which the carbonated water has acted more readily, perhaps because the chalk happened to be more soluble in those places, or because the slope of the surface favoured the concentration of the water at certain points. Or, as is frequently the case, the pipes may occur upon the lines of joints or other natural fissures. In such pipes the included flints are usually found standing on end—the position which they would naturally assume during the slow subsidence of the clay and rubble, caused by the gradual dissolution of the chalk and consequent deepening and widening of the pipes.

In common limestone, which is a harder rock than chalk, similar pipes occur along the lines of joints, and are often continued downwards until they reach the roof of some underground gallery. The pipes being open now at both ends, any materials which they may have contained find their way eventually into the gallery or cave below, and new channels of communication with the surface are thus opened. Now and again the limestone forming the roof of a

cave, becoming loosened by the action of percolating water along the joints, falls in, and a more or less wide *sink* is formed, through which water, soil, and detritus, and animals and plants, or their débris, may be introduced to the underground gallery.

2. **Mechanical Action.**—Although it cannot be doubted that some caves and cave-like hollows have been eaten out entirely by the chemical action of acidulated water, yet in many cases the widening of subterranean galleries must be largely the result of the mechanical action of running water. We know that in calcareous regions underground streams and rivers are of common occurrence. Thus the Sorgue, one of the tributaries of the Rhone, issues as a goodly river from a spacious cave at the base of a precipice of calcareous cliffs. Even in the dry season the body of water here poured forth has been estimated at 13,000 cubic feet a minute, and after heavy rains this volume is increased fourfold. The affluents of this stream are not known, their course being entirely underground, but they are supposed to take their rise in a dry arid plateau of limestone some twelve or fifteen miles away. Another good example of a subterranean river is that which, under different names, traverses the famous caves of Adelsberg, Planina, and Upper Laibach in Carniola. This river (the Poik), after flowing for some five or six miles underground, where it receives the tribute of another underground stream, emerges only to disappear after a short distance in a second underground course, from which it finally escapes and eventually empties itself into the Danubian Save. Some subterranean rivers never appear at the surface, but reach the sea by underground channels. The phenomenon of fresh-water brooks and springs issuing on the bed of the sea is in fact far from uncommon, and some of these occur at considerable depths. Thus it is said that certain springs rise on the sea-bed off the coasts of Provence and Liguria at depths of as much as 500 and 900 feet, and that a stream of fresh water pours out upon the floor of the sea some four miles south of Cape Saint Martin at a depth of over 2000 feet from the surface. Similar submarine springs probably abound off the coasts of most countries where calcareous strata form the prevalent rocks, and after heavy rains their influence is sometimes sufficient to render the sea-water brackish. This was the case off the coast of Florida in January 1857, when the discharge of fresh water upon the sea-bottom was so great that the saltness of the sea was diminished by one-half, while myriads of dead fishes floated on the discoloured and muddy water, and accumulated on the shores.

The mechanical action of such bodies of water must be considerable, and we cannot doubt therefore that the underground galleries through which they flow have been widened and deepened by

simple attrition. Rocks falling from the roofs, and rock-rubbish introduced by pipes, swallow-holes, sinks, etc., are rolled forward, becoming rounded in the process, at the same time that the limestone over which they are swept is gradually eroded, and the channel of the stream deepened and widened. Underground rivers not infrequently desert their channel for a new course. Many causes may bring about such changes. Sometimes the water may be gradually drawn off by lateral fissures, as these are widened by chemical and mechanical erosion, until the whole stream finds a more direct passage to a lower level. It is probable also that similar changes may be induced by sudden falls of rock from the roof of a gallery which, by blocking the passage, may dam back the stream and force it into other fissures, and these latter becoming sufficiently deepened, the old course may finally be abandoned in their favour. Other causes for changes in underground drainage may be found in earthquakes, which might readily bring about the collapse of wide underground hollows and more or less revolutionise the whole drainage-system of a wide region.

Deposits formed in Caves and Underground Galleries.—We know from actual observation that the course of an underground stream is not only very tortuous, but that the slope of its bed is usually very unequal. Dr. Schmidt, who was the first to sail up the underground course of the Poik, describes it as a succession of rapid streams, cataracts, and quiet lakes. It is evident then that in the course of such a river we may have accumulations of coarse and fine sediment. Gravel and shingle will be hurried forward over the steeper parts of the course and accumulate at the heads of the lakes, while finer sediment will tend to gather over the lake-beds beyond the limits reached by the coarser detritus. This detritus will be composed largely of limestone-fragments, but now and again other kinds of rock-rubbish and much organic débris may be introduced from the outside by the river itself as it plunges underground, or by occasional rains or flooded torrents washing down through sinks and swallow-holes. Now and again, too, animals may fall into such openings, and their remains become commingled with the gravel, sand, and mud which are swept forward and accumulated in the deeper and quieter hollows of the subterranean channels. Should such channels afterwards be deserted by the stream then stalagmite will be gradually deposited upon the floors of the underground galleries. In course of time such galleries may become more or less accessible from the outside, when they may form the haunt of carnivorous animals, who will carry thither their prey, and thus by and by accumulations of bones will be formed, which the drip of water from above may gradually enclose

in calcareous matter and eventually cover up under a sheet of stalagmite. After having been the haunt of wild beasts for a longer or shorter period, running water may again find its way into the gallery and lay down deposits of gravel, sand, loam, or clay upon the stalagmite. Or the stalagmite, together with the bones covered by and enclosed within it, may be broken up and partially or wholly removed. Once more the stream may disappear and newer accumulations of bones and stalagmite may be formed. Commingled with the stalagmitic material there will probably always be more or less of reddish earth or clay—the insoluble residue of the calcareous rock (see fig. 6).

Local Subsidences and Rock-falls.—Some account has been given of the formation of sinks and swallow-holes in calcareous rocks. It not infrequently happens that the dissolution and removal of rocks by the chemical and mechanical action of underground water leads to considerable disturbances of overlying strata. While thick masses of rock-salt, for example, are being dissolved and removed, the superjacent strata gradually subside, and are in consequence thrown into confusion—being bent, crumpled, fractured, and contorted, just as if they had been subjected to the action of subterranean forces. Such local subsidences may of course take place suddenly. The soluble rocks may be removed without the simultaneous subsidence of the overlying strata. Eventually, however, the great strain upon these latter causes them suddenly to collapse, and more or less extensive *rock-falls* or sinks, as the case may be, are the result—whole hill-sides tumble down in ruins, or the surface of the ground is locally depressed. The evidence of such catastrophes having taken place is conspicuous in many regions where limestone, gypsum, dolomite, and rock-salt are of common occurrence. Thus, rock-falls caused by the removal of gypsum are well seen at the foot of the Thüringerwald and along the south-west borders of the Harz. In the same regions are many small lakes formed by local subsidences.

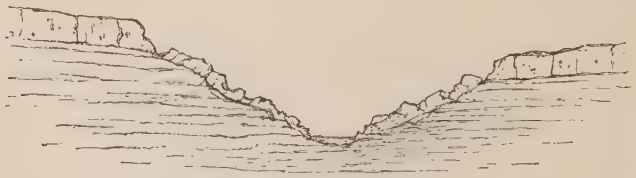


Fig. 8.—Landslips. Sandstone slipping over shale. (R.)

Landslips are generally caused by the action of underground water upon rocks of variable character, so arranged as regards

their geological structure that when any underlying portion has been rendered soft and incoherent or weakened by the dissolution and removal of some of its substance, gravity comes into play, and the overlying portion slides forward or topples down (fig. 8). Such catastrophes are of most frequent occurrence in regions where the strata are composed of alternations of permeable and impermeable rocks. In such regions landslips of larger or smaller size are liable to occur along sea-coasts and in river-valleys whenever the strata are inclined towards these. The accompanying section (fig. 9) will help to make this clear. We have here a section of porous beds (*a a a*) and impermeable beds (*b b b*)—the inclination of the

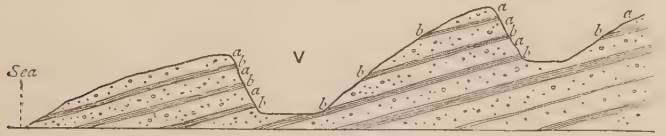


Fig. 9.—ORIGIN OF LANDSLIPS.
a a, Porous strata; *b b*, impermeable beds; V, valley.

strata being towards one side of the valley (V) and the sea-coast. Water percolating down through the porous beds (*a a*), which we may suppose are sandstone, is arrested by the impermeable beds (*b b*), which we shall say are clays. These latter become in course of time lubricated and rendered slippery, and the overlying sandstones, perhaps many hundreds of feet in thickness, are by and by set in motion by gravity, slide downwards, and fall in ruins into the valley and upon the seashore. The great fall of the Rossberg (Switzerland) on September 2, 1806, was induced by conditions similar to those represented in the diagram. This catastrophe took place at the close of a very rainy season. The rain percolating through the porous rocks above had converted the underlying clay beds into a kind of mud, the result being that the undermined rocks began to slip forward gradually, and then in a moment gave way and rushed downwards into the plains of Goldau. The slipped portion measured $2\frac{1}{2}$ miles long, by about 350 yards wide and 35 yards thick, and has been estimated to contain more than 54 millions of cubic yards.

CHAPTER IV.

GEOLOGICAL ACTION OF TERRESTRIAL WATERS—*continued.*

Brooks and rivers, chemical action of—Mechanical action of—Attrition of stones by running water—Excavation of river-channels—Forms of river-ravines—Cascades and waterfalls—Narrow gorge and wide valley—Process of valley-formation—Transport of sediment—Deposition and accumulation of sediment in bed of river, in lakes, in the sea—Bars opposite mouths of rivers—Deltas.

III.—BROOKS AND RIVERS.

1. Chemical Action.—River-water no doubt acts directly as a solvent upon some of the rocks over which it flows. This is conspicuous in the case of rocks which are largely composed of carbonate of lime (limestone, chalk, etc.), or of sulphate of lime (gypsum). But the mineral matter carried in solution by rivers is unquestionably derived in largest measure from springs and underground sources. Nevertheless, the action of running water upon certain felspathic rocks (such as granite) tends to show that considerable chemical decomposition is carried on in the beds of brooks and rivers. The felspar of those rocks is decomposed—with the result that certain substances (such as potash and soda) are removed in solution as carbonates, and a fine insoluble clay is left to be swept onward as a sediment.

The nature of the matter carried in solution by rivers depends, of course, upon the geological character of the drainage-area. Thus in highly calcareous regions the rivers always contain a large proportion of calcium carbonate—the water is said to be *hard;* while in districts composed of less soluble rocks the proportion of matter in solution is small—the water is *soft.* For example, it has been shown by chemical analyses that the rivers in those of our upland districts which are largely composed of igneous rocks, contain the smallest proportion of matter in solution—an average of many streams giving a total of 5·15 in 100,000 parts of water. The upland waters of our "mountain limestone" regions, however,

contain as much as 17·07 of dissolved matter in 100,000 parts of water.

The substances usually held in solution in our rivers are:—

Carbonates of lime, magnesia, soda, iron, ammonia.
Silica.
Peroxides of iron and manganese.
Alumina.
Sulphates of lime, magnesia, potash, soda.
Chlorides of sodium, potassium, calcium, magnesium.
Silicate of potash.
Nitrates and nitrites.
Phosphoric acid.
Organic matter.

Of these as small a percentage as 2·61 in 100,000 parts of water have been observed; but they sometimes reach as much as 50 or 60 parts in 100,000. The most abundant substance is carbonate of lime, forming as much as half of the whole matter in solution. Next in order comes sulphate of lime, which in rivers flowing over gypseous strata often forms as large a proportion of the dissolved matter as carbonate of lime does in the rivers of highly calcareous tracts.

The amount of material thus carried may appear relatively small; but when we consider the size attained by many rivers we perceive that in course of time enormous quantities of dissolved substances must be borne into the sea. Rivers like the Rhine, the Danube, the Elbe, and the Rhone, which contain in every 6000 parts by weight 1 part of dissolved mineral substance, will transport seawards their own weight of the latter in 6000 years. Reflecting upon such facts we cannot be surprised at the extent of the caves and underground galleries of calcareous regions, or at the numerous local subsidences, rock-falls, and landslips which have taken place as the result of the chemical action of running water.

2. Mechanical Action.—Pure water, *i.e.* water containing a minimum of sediment in suspension, has comparatively little erosive power. Other things being equal, a river carrying much sediment will erode or wear away its channel more rapidly than a clearer stream. It is the sediment, then, set in motion by the water which causes what is known as aqueous erosion.

1. Mutual Attrition of Stones, etc., in Running Water.—Let us consider first the action of the moving detritus or sediment upon itself. The stones which one sees in the bed of a brook have of course been derived from the rocks of the valley in which the water flows. They may have been showered down from banks or cliffs by the action of rain, springs, or frost, or they may have been

dislodged by the undermining action of the stream itself. The stones, when they are first introduced, are more or less angular, but as they are carried or rolled forwards the sharp corners and edges get worn away by attrition, and they eventually become more or less rounded. In the steeper and rocky parts of a river-course much of this attrition is caused by the stones being brought more or less violently into contact with the irregular rock-surface over which they are forced. In less inclined portions of the channel the stones and grit tend to collect and spread themselves over the bed of the stream, and the attrition which they undergo in such positions is chiefly the result of mutual rubbing as they are rolled over and against each other. This mutual rasping and rubbing gives rise to finer-grained sediment, grit, sand, etc. Thus in a typical river-course, consisting of mountain-track, valley-track, and plain-track, we note a progressive change in the character of the sediment as we follow the river from its source to the sea. In the mountain-track angular and subangular blocks and smaller fragments abound, and the detritus generally is coarse and irregularly distributed over the bed of the stream. In the valley-track well-rounded gravel with grit and sand predominate, the latter becoming relatively more plentiful as we approach the plain-track. In the plain-track the prevailing sediment is fine sand and silt. As a rule the finer-grained materials show less trace of rounding than the stones and coarser grit, so that it is only partially true that the farther the sediment travels the more water-worn it becomes. As soon as the particles are small enough to be carried in suspension they escape in large measure the attrition to which the gravel-stones and coarse grits are subjected upon the bed of a river.

2. Action of Sediment upon Rocks of a River's Bed.—This is most strikingly displayed in the mountain-track. In the beds of torrents one may often see stones and large blocks in more or less rapid motion. Occasionally these are carried forward with such violence that when they come into collision with other blocks or irregularities in the channel they leap out of the water. Stones measuring one foot and more in diameter have in this way been thrown out upon their unsubmerged banks by some torrents in the Scottish Highlands. In the torrents of the French Alps large blocks are sometimes hurled out of the bed of the stream to a height of twelve or thirteen feet. The thunderous roar of such torrents is caused chiefly by the battering of the stones as they leap and roll along. And so great is the attrition thus caused in the Southern Alps that the "atmosphere of certain valleys where the limestones are bituminous has at times of flood the marked bituminous smell produced by rubbing pieces of such limestone

together." Under the assaults of such stones and blocks the rocky beds of torrents are rasped, filed, rubbed, smoothed, and furrowed, the erosion being of course most marked in places where the rocks yield most readily.

In many parts of rapid-flowing streams, as at the foot of waterfalls, the stones have frequently a gyratory motion imparted to them by irregular movements of the water. As they rotate they gradually wear away the rock and produce more or less steep-sided cavities or *pot-holes*. Occasionally a number of such pot-holes occur in close proximity, and as each is widened by the grinding action of the rotating and revolving stones, the dividing partitions are eventually worn away, and more or less winding, irregular trenches or gullies are formed.

Speaking generally, the erosive power of a river progressively diminishes with the lessening inclination of its bed. In its upper course it receives the wreck produced by frosts and torrents, and with the aid of these grinds down the naked rocks. In its middle and lower courses, however, it is more largely employed in getting rid of the materials derived from its upper course. In its upper course, therefore, the water usually flows through trenches and ravines excavated in the solid rock. Such ravines are generally less conspicuous in the valley-track, while in the plain-track they do not exist.

3. Form assumed by River Ravines, etc.—The ultimate form assumed by river-trenches and ravines depends largely upon the character and structure of the rocks. If these are more or less homogeneous and arranged in horizontal beds the tendency of the river is to cut a steep-sided trench (see fig. 10). This characteristic action is very well seen in the steep trench-like valleys of the

Fig. 10.—River-ravine in horizontal strata.

Fig. 11.—River-ravine in massive crystalline rocks.

Faeröe Islands, where the strata consist of basalt and tuff (lava and volcanic dust, etc.) disposed in approximately horizontal beds. But a still better example is afforded by the great chasm through which the Colorado river flows. This chasm is some 300 miles in length; its walls are approximately vertical, and vary in height from 3000 feet to 6000 feet. The river is aided in its erosive work by the natural joints or fissures in the rocks, which, being at right angles to the planes of bedding, are of course vertical, so that when the strata

are undermined they give way along those lines of weakness, and leave a new vertical face exposed. The rainless character of the district also tends to prevent the breaking-down of the rock-walls. Were the strata much subjected to the action of rain and frost, springs coming out along the lines of bedding, and frost acting within the joints, would cause the rock-walls to recede more rapidly, and the upper portion of the cliffs would retreat, as it were, more readily than the lower—the latter being protected by the accumulations of débris derived from the demolition of the rocks above. Thus in process of time the steep rock-walls would tend to disappear, and to be replaced by long curtains of rock-rubbish, sweeping down at a more or less steep angle from the upper limits of the valley of erosion.

The form assumed by river-trenches, being thus dependent upon the nature of the rocks and the character of the climate, is very variable. In massive crystalline rocks which are often very irregularly jointed, the ravines excavated by water-action generally show rough and irregular walls (fig. 11); occasionally these are steep, and in places even overhanging; sometimes they are replaced by débris-covered slopes, above which isolated knobs and crags may project. In short, in the case of such rocks, we may have almost any variety of configuration. If we examine the cliffs in such ravines we shall rarely see any trace of watery erosion upon their flanks. Here and there at some considerable height above the

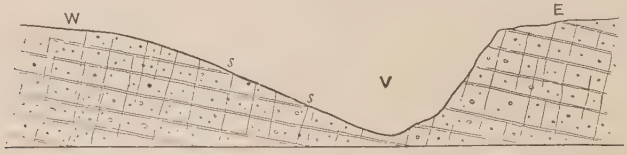


Fig. 12.—SECTION OF RIVER-VALLEY IN INCLINED STRATA.
V, Valley; *s s*, springs.

present stream one may note pot-holes, and now and again a smooth and well water-worn surface, indicating former water-levels; but these are exceptional. As a rule the surfaces we see are defined by natural joints and fissures, and the rock is more or less weathered. The present cliff-faces have been produced by the combined action of rain, springs, frosts, and so forth. It is by means of these agents that the cliffs are compelled gradually to retreat, as one might indeed infer from the heaps of loose angular rock-rubbish that extend from their base downwards to the river.

In the case of bedded rocks, the dip or inclination of the strata often greatly influences the character of the ravines. If, for

example, the strata are inclined into a valley we shall have a more or less steep cliff on one side of the river and a more or less gentle slope on the other. The reasons for this contrast will be readily understood from the diagram (see fig. 12). Here we see a series of strata dipping into the valley V which is shown in cross-section. It is obvious that the structure of the strata will favour their demolition on the west side (W) of the valley, while it will enable them better to withstand the agents of waste on the east side (E). Springs (*s s*) coming out along the lines of bedding and frost acting within the joints on the west side of the valley will tend to produce miniature rock-falls and landslips. But on the east side the subterranean drainage is *away from* and *not into* the valley, and therefore less surface-waste can be effected. This structure is well shown in the valley of the Esk between Roslin and Hawthornden. There the river flows through a series of grits and sandstones, the dip of which changes about from one side to the other ; and with every change of dip or inclination we have a corresponding change in the position of the cliffs, which shift about, as it were, from one side of the river to the other.

4. Cascades and Waterfalls.—If rivers flowed over homogeneous rock-masses that yielded equally throughout to erosion,

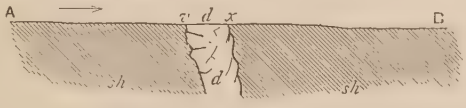


Fig. 13.—origin of cascades.

there could be no cascades or waterfalls. These result from the fact that rivers often traverse rocks of very variable character—some being much less easily eroded than others. Such being the case, the rocks yield unequally to the action of the water and irre-

Fig. 14.—origin of cascades.

gularities arise. If, for example, we have in the bed of a river a series of crumbling shales (*sh*), traversed by a hard igneous crystalline rock (*d*), the shales at *x* will wear away more rapidly than the latter, and a cascade or waterfall will tend to be produced. The river we shall suppose flows at first along the line A B (fig. 13). The shales at *v* cannot be greatly eroded so long as the rock *d* is able to withstand the action of the water ; they will only

be removed by slow degrees as the surface of *d* is lowered by erosion. Between *x* and B, however, they have no such protecting influence, and consequently they will be more or less rapidly eroded there. By the lowering of their surface a waterfall will eventually be formed at *d*, and then we shall have such a section as is seen in fig. 14.

It can be shown that many ravines have been formed by the slow retreat of waterfalls. Such is the origin of the deep river-trench that extends from Queenstown to the Falls of Niagara. The strata in this river-trench consist of beds of sandstone, shale, and limestone, which incline at a low angle up the valley. A glance at figure 15 will show that the falls take place from the edge of the limestone, a comparatively hard rock, which is underlaid by less

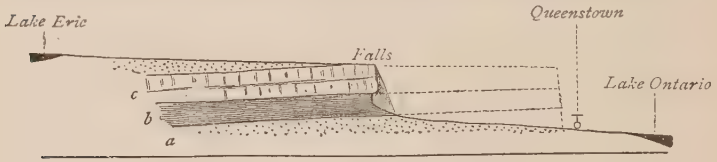


Fig. 15.—FALLS OF NIAGARA.
a, Sandstones, etc.; *b*, shales; *c*, limestone.

coherent beds of shale. These latter wear away much more readily than the overlying limestone, so that the latter becomes undermined, and from time to time large portions give way along the lines of natural joints and fissures and fall to the bottom. In this way the waterfalls have gradually retreated for a distance of seven miles. As the strata dip or incline towards Lake Erie, the falls must decrease in height as time goes on, until eventually the shale ceases to appear at the bottom. The limestone will then be less readily undermined, and the great falls will gradually be replaced by a series of broken *rapids* extending back to the point of outlet from Lake Erie.

5. NARROW GORGE AND OPEN VALLEY.—The fact that rivers for the most part flow over rocks of unequal durability sufficiently accounts for that succession of narrow gorges or ravines and open or wider reaches which is characteristic of so many valleys. The gorges mark the position of the more durable or less easily eroded rocks—the wider portions of the valley have been excavated in rocks which have yielded most readily to the action of the river and its allies—rain, springs, and frost. The walls of the gorges are more or less steep, and they retreat slowly, as it were. The wider valley, on the other hand, is bounded not by steep cliffs but by long gentle slopes, which, constantly cut into by the river as it

winds from side to side, are again and again renewed by the action of the other subaërial agents. Thus a river erodes not only vertically but laterally, the form assumed by its valley being due to the relative resistance of the rocks.

6. The Process of Valley-formation.—The tendency of all rivers, as we have seen, is to reduce their beds to one common gradient. Thus the plain-track is ever slowly extending inland, while the valley-track in like manner gradually encroaches upon the mountain-track. At the head of the mountain-track, again, we see that the numerous springs and rills that collect to form the young river are ever eating their way back into the mountains from which they flow. The general cutting back of a valley is well illustrated by what one sees taking place in the valleys of the Faeröe Islands. A section drawn across one of those islands along the line of two valleys descending seawards in opposite directions shows the general features expressed in the accompanying diagram (fig. 16). The rocks consist of a succession of basalt-beds separated by thinner layers of tuffaceous clays and shales, which are somewhat impermeable, while the basalt being much jointed

Fig. 16.—SECTION ACROSS ONE OF THE FAERÖE ISLANDS.

is readily traversed by underground water. Advancing up the valley W from the sea, we find the stream flowing down a gentle slope formed by the surface of a bed of basalt. At c^1 we encounter a wall of rock formed by the outcrop of another bed of basalt over which the stream precipitates itself. Ascending this cliff we come upon a second gentle slope, which in like manner terminates against a second cliff with its cascade at c^2. Above this second cliff a third gentle slope succeeds and reaches back to the base of a steep precipice p. Crossing the ridge above we descend the valley E by a succession of gentle slopes and intervening cliffs, which are similar in all respects to those of the valley W. Both valleys are flanked by lofty and precipitous cliffs which are indicated by the dotted line. Now these deep gorge-like valleys have evidently been formed by the retreat of the cascades and waterfalls. The basalts are readily undermined by the action of springs which come out along the line of the clays and shales, and this action is of course largely aided by frost. It is evident, however, that some beds of basalt will be eaten back more readily than others. The

cascades formed by such basalts will therefore gradually draw up, as it were, until they coalesce with cascades which are retreating at a slower rate. Again the presence of a peculiarly impermeable bed and the outflow along such a bed of a strong spring will induce a correspondingly excessive erosion. The overlying basalt-bed will be rapidly undermined, and its fall will cause all the beds above it to give way. Such we may suppose to have been the origin of the great cliff *p*. By the retreat of this cliff and the corresponding smaller cliffs in the valley E, it is evident that in course of time the intervening ridge will be demolished, and a deep hollow extending from sea to sea across the island will be produced. Several such hollows, indeed, have actually been completed, so that one can traverse certain islands from sea to sea, advancing inland by a long gentle slope to the waterparting, often a low-lying flat moory tract, and then descending seawards by a similar low gradient.

In regions where the mountains are built up of different kinds of rock—some bedded and others massive—and all more or less confusedly disposed, the forms assumed by the valleys towards their points of origin are necessarily varied. Thus we perceive that it is the character of the rocks and their geological structure that determines the form assumed by a river-valley from the mountain in which it takes its rise down to the point at which the river ceases to erode.

7. Transport of Sediment.—The quantity of sediment removed by a river is not always proportionate to the volume and velocity of the water. In some African rivers there is as much sand as water, and in the Rocky Mountains certain valleys are filled with thick sheets of earthy débris which when soaked with water move slowly forwards with a sluggish motion like glaciers. Rivers that flow through lands composed of rocks which are readily eroded will, other things being equal, transport more sediment than rivers coming from tracts where the rocks yield less easily to aqueous action. It is in their mountain-tracks that rivers are most active as eroding and transporting agents. Owing to their greater velocity in those regions they are enabled to carry forward quantities of material which are out of all proportion to their volume. This is well seen in the action of mountain-torrents which sweep downwards immense heaps of débris. No sooner, however, do they reach low ground than their velocity is checked and the coarser sediment is at once thrown down. In this way *cônes de dejection*, as they are called, of relatively large size, are formed where such torrents suddenly emerge upon plains or open valleys. Ancient cônes of this character occur in many parts of Europe which are far beyond the power of the existing torrents to accumu-

late. These latter are now engaged in digging trenches through the older cônes, and forming newer and less extensive cônes at lower levels.

The large size of blocks pushed along its bed by a river in flood is often remarkable. But we must remember that stones lose in water a third or a half of their weight, and that some stones owing to their shape are more readily pushed forward than others. Round stones it is evident will be moved more easily than flat ones ; and smooth ones will slip along more readily than those that are rough and angular.

It is during times of flood that the transporting power of rivers is at its maximum. Ordinary floods occur periodically during the rainy season, or they may be due to the melting of snow. More water is at such times poured into a valley than can at once be drained off ; so that a series of temporary lakes are formed, and these are connected by narrow gorges which are choked with torrential waters. Rivers flowing from temperate to arctic regions are also periodically subject to floods. The ice of the far north continues to bind those rivers for some time after their icy chains have been removed in the south, and hence wide tracts become flooded. Again floods may be caused by the temporary choking of ravines by accumulations of floating-ice or of drift-wood, or by the advance of a glacier across the mouth of a lateral valley. In each of these cases a temporary lake is formed above the obstruction, which sooner or later gives way more or less suddenly, with the result that the lake is at once emptied, and the scouring and transporting power of the river enormously increased. The bursting of the ice-barrier of the Bagnes, one of the largest tributaries of the Rhone above the lake of Geneva, produced a flood that started with a speed of 22 miles an hour, and resembled for the greater part of its course a moving mass of mud and rocks —some of which were as large as houses.

The quantity of insoluble matter carried in suspension by a river and rolled forward upon its bed naturally varies according to the season of the year. During the rainy season it is of course greater than when the water is low. The amount of sediment will also vary according to the character of the rainfall. If this be distributed over the whole year the rivers may remain comparatively clear, whereas the same amount of rainfall crowded into a short rainy season, may convert the rivers into torrents and floods which will sweep away in a few days much more material than the same quantity of water equally distributed over a year could transport in that time.

Were we to estimate the amount of material required to fill up

valleys of erosion so as to restore the surface on which the rivers first began to flow, we should be able to form some estimate of the great thicknesses of rock which have within comparatively recent geological periods been removed by aqueous action. And we may even form some approximate notion of the time required for the erosion of such valleys by measuring the amount of sediment which rivers are transporting yearly to the sea. Thus it has been estimated that the material carried in suspension by the Mississippi during one year would weigh as much as 812,500,000,000 of pounds, while some 750,000,000 of cubic feet of sediment are pushed along the river's bed. Again, the Ganges transports annually 6,368,077,440 cubic feet of sediment—for the carriage of which, as Lyell computes, a fleet of 2000 Indiamen, each of 1400 tons burthen, would require to start every day throughout the year.

8. Deposition and Accumulation of Sediment in Bed of River.—Erosion is at a maximum and deposition at a minimum in the mountain-track of a river. Hence many rivers which descend more or less abruptly from mountains and elevated plateaus to the sea accumulate but little sediment in their courses. In the valley-track deposition often equals erosion, while in the lower or plain-track deposition as a rule is in excess of erosion. During the ordinary flow of a river, gravel and sand and silt are continually passing along the channel—the sediment becoming finer as the gradient diminishes. Very little of this fine sediment is allowed to accumulate in the channel or water-way of the valley-track—the current as a rule being too strong. But during times of flood, when the wider parts of the valley become converted into temporary lakes, considerable depositions of mud or loam may take place over the flooded areas ; and in this way alluvial plains are gradually formed. As the river deepens its channel the time comes when it is no longer able to flood those plains, and it then commences to erode them, winding about from side to side of its valley, and gradually forming new flood-plains at a lower level. Hence, in course of time, we may have a number of terraces (composed of gravel and sand and overlaid by flood-loams) occurring at different levels upon the slopes of a valley.

The appearances presented by many river-valleys in Britain show that while many old alluvial terraces have been formed in this way, yet a number of well-marked benches and flats require a different solution. Our rivers appear formerly to have flowed in larger volume and to have covered wider areas—so that in many places the valleys were filled to a considerable height with fluviatile accumulations. In more recent times the rivers, reduced in size,

have been largely engaged in re-excavating those old accumulations, and in forming a succession of terraces at lower levels. The general disposition of the terraces referred to is shown in the accompanying diagrammatic section (fig. 17). At the bottom the

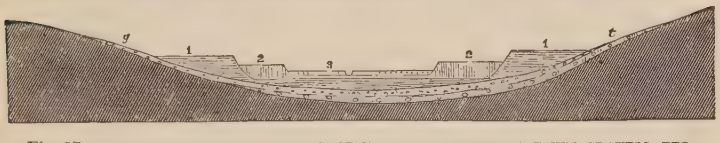


Fig. 17.—DIAGRAMMATIC SECTION OF POST-GLACIAL AND RECENT RIVER-GRAVELS, ETC.
g t, Glacial accumulations; 1, 2, 3, successive terraces of alluvial origin.

solid rocks are covered with glacial accumulations *g t*, above which come the deposits of terrace 1, formed at a time when the river was able to flood the whole bottom of the valley. The later terrace 2 has been formed, as will be seen, in a hollow excavated out of the deposits of terrace 1; while the deposits of the existing river, forming terrace 3, have in like manner been laid down in a hollow dug out of terrace 2.

Accumulations of sediment often take place at the point where a river is joined by a tributary stream. When one or other is in flood its waters receive a sudden check upon encountering the more placid flow, and a deposition of sediment is the result.

9. DEPOSITION AND ACCUMULATION OF SEDIMENT IN LAKES.—A river entering a lake receives a still more complete check, and its transporting power is immediately reduced. Consequently its heavier materials are at once thrown down, the sediments being gradually sorted out as the rate of flow diminishes. If the lake be sufficiently extensive only the very finest mud and silt will be deposited at any distance from the shore.

10. DEPOSITION AND ACCUMULATION OF SEDIMENT IN THE SEA.—Opposite the mouths of rivers entering the sea *bars* of gravel, sand, and mud are often formed. These are frequently made up almost entirely of material brought down by the rivers. In many cases, however, they owe their origin partly to the action of the sea—the tides and currents tending to throw up bars across the mouths of narrow estuaries, even where there is no river-action to speak of. Such barriers are constantly being modified—sometimes by the rivers, and at other times by the sea during storms. But the most important fluviatile deposits of maritime districts are those broad flats which are called *deltas*. They are best developed upon the shores of comparatively sheltered seas. In such seas, indeed, estuaries are somewhat uncommon: these have been silted up and we find deltas in their place. On the other hand, along exposed

sea-boards, estuaries are common and deltas are somewhat rare. A typical delta, such as that of the Nile, is triangular in shape, resembling the Greek letter Δ, which resemblance indeed is the origin of the name. The apex of the triangle points up the valley, and its base faces the sea. We can readily understand why this should be when we remember that the delta simply occupies the position of an estuary. In former times the Nile must have entered the sea near Cairo, and all the flat tracts through which its branches meander to the Mediterranean have been gained from the latter by the gradual growth of fluviatile sediment. A river very often divides into two or many branches when it enters its delta. This is owing to the very gentle inclination of the ground —the slightest accumulation of sediment or impediment to the flow of the water sufficing to divide and divert the current in different directions.

The character of the sediment carried down to a delta varies with the season of the year. When the river is low only the finest sediment may find its way into the delta and out to sea, while, during flood, coarser materials will be transported seawards, and wide areas becoming inundated will be coated with a covering of fine loam or mud. But the general character of the sediment will be determined by the transporting power of the river. Should a broad stretch of low ground and gentle gradients separate the middle reaches of the river from the sea, then fine-grained sediment will predominate in the delta. On the other hand, should the river descend by a steep course to the sea, the detritus composing the delta will consist largely of gravel and sand. The growth of a delta seawards depends partly upon the activity of the river, and partly upon the depth of the estuary, and the action of tidal currents, etc. A shallow estuary will be more readily silted up than one that is deeper ; and a delta will increase more rapidly in a comparatively closed bay where the tide is moderate, than in an open sea where the action of waves and tides is more pronounced. The progress of the delta of the Nile is impeded by a tidal current which sweeps along the coast, while the delta of the Mississippi as it advances will be limited by similar strong tidal currents, and by the increasing depth of the sea. Within the last 2000 years the average annual increase of the delta of the Po has been 55 feet. In recent times, however, its growth would appear to have been more rapid, the annual increase amounting to 76 yards. This more rapid advance is supposed to be caused by the artificial embankment of the river which compels the current to carry seawards the whole of its alluvium. The delta of the Rhone is also advancing rapidly. In the fourth century the town of Arles

was only 16 miles from the sea, now it is 29 miles. This gives an increase of 13 miles in fourteen centuries, or about 52 feet in a year. This advance is exceeded by that of the delta of the Mississippi, which varies from 86 to 110 yards annually. But, as just remarked, the increasing depth of the sea will by and by prevent so rapid a growth.

The deposits of which a delta is composed are apt, as we have seen, to vary in character. They are generally arranged in more or less thin beds or layers, and these usually thicken and thin out irregularly. Now and again they show deeper accumulations of one and the same kind of sediment, which, when fine grained (loam, clay, etc.), is generally disposed in even layers. When the sediment is coarser (sand and grit) the beds are apt to be less equally arranged—the layers of which they are composed indicating more or less rapid changes in the direction and velocity of the current. At low tide wide flats of mud and clay, often ripple-marked, are left exposed, and over these birds and other creatures wander in search of food, leaving their footprints behind them. The same surface may also be marked by rain-pits, and cracked and fissured as it dries up under the heat of the sun. When the next tide comes in all those superficial markings may be gently covered up by a fresh deposit of fine mud or sand, and so become preserved. Again, wide areas of a delta clothed with vegetation may be submerged during excessive floods and buried under newer accumulations of sediment. We know also that numerous relics of animal- and plant-life are carried down from time to time by a river, so that the whole series of deposits occupying its partially silted-up estuary must be more or less charged with remains of the fauna and flora of the adjacent land. Now and again, too, the deposits will show comminglings of fresh-water or brackish-water and marine organisms. During storms or extra high tides the sea sometimes advances rapidly upon a delta, demolishing in a few hours the fluviatile work of years, and thus marine creatures are enabled for a time to reoccupy the area over which they had formerly lived. Again, sand-dunes are often formed along the seaward margin of a delta, and these occasionally during floods act as dams, keeping back a portion of the water, which subsequently forms a fresh-water lagoon. Such lagoons tenanted by fresh-water organisms may endure for some time; but eventually the sea may invade and occupy them. In this way marine organisms will be introduced, and should the lagoons be afterwards silted up, certain layers of sediment would contain a commingling of marine and fresh-water forms. Finally, in all estuarine deposits we shall expect to find some more or less decided trace of a passage from fresh-water

to marine conditions. Fresh-water beds, charged with terrestrial and fresh-water organic remains, when followed along one and the same horizon, will eventually graduate into strata containing a more or less abundant suite of marine organisms, together with, it may be, a few relics of terrestrial life which have been drifted out to sea.

CHAPTER V.

GEOLOGICAL ACTION OF TERRESTRIAL WATERS—*continued.*

Lakes, fresh-water and saline—Fresh-water lakes—Obstruction lakes—Crater lakes—Sink lakes—Earth-movement lakes—Glacial lakes—Lakes as receptacles of sediment—Salt lakes, deposits formed in—Erosion along margins of lakes—Existing lakes are all of recent geological age.

IV.—LAKES.

Lakes are of two kinds—fresh-water and saline—and have originated in various ways. Of many the origin is obvious enough, but there are others which it is sometimes difficult to account for. No classification of lakes can pretend to be more than one of convenience for purposes of description. Taking first the fresh-water lakes, these may be roughly grouped as follows :—

1. Fresh-water Lakes.—1. Obstruction Lakes.—(*a*) *Lakes formed by temporary obstructions.*—In this class may be included certain lake-like expansions of rivers, which often disappear in the dry season when these are low. The more or less temporary sheets and pools of water which occupy the deserted loops of a river channel, together with those that appear after floods in the shallow depressions of an alluvial plain, come under the same head. The operations of the beaver also give rise to temporary lakes. Again drifted vegetable débris by choking the narrower passages in a river will cause the water to flood the more open valley above ; and a similar result may be brought about by river-ice. Lastly, the advance of a glacier across the mouth of a lateral valley forms a dam behind which a temporary lake will appear. The bursting of such more or less frail barriers has been the frequent cause of destructive floods. (*b*) *Lakes formed by more durable obstructions.*—Occasionally rock-falls and landslips obstruct the drainage of valleys and give rise to lakes, and similar results will follow from the advance of a sheet of lava across a valley. The persistence of lakes of this class depends of course upon the nature and extent of

the obstruction. Some may endure for many years, and so allow of considerable lacustrine deposits taking place.

2. Crater Lakes.—These are lakes which occupy the craters of extinct or quiescent volcanoes. They are not uncommon in volcanic regions. Amongst European examples are the lakes of Averno, Bolsena, and others in Italy, and the Laacher See and the Maars of the Eifel in Germany.

3. Sink Lakes.—The lakes of this class lie in hollows caused by subsidence of the surface consequent upon the removal of underlying soluble rocks. These often abound in regions of calcareous and gypseous rocks, or where rock-salt occurs. They are generally of small size.

4. Earth-movement Lakes.—Unequal movements of the earth's crust have occasionally originated hollows by direct subsidence ; and it is possible that partial elevation by affecting the lower ends of valleys may sometimes have obstructed the flow of rivers, and thus given rise to lakes. But no example of a lake formed in this latter way can be cited. The great African lakes probably occupy hollows formed by direct subsidence.

5. Glacial Lakes.—These are of two kinds : (*a*) *Hollows of erosion* or *rock-basins* which have been excavated by glacier-ice ; and (*b*) *Hollows caused by the unequal distribution or accumulation of glacial detritus.* A more particular account of these lakes will be given later on.

It is as receptacles of sediment that lakes are of most importance from a geological point of view. Deltas are formed by torrents, streams, and rivers entering a lake much in the same way as maritime deltas are accumulated. Many lake-basins have indeed been completely silted up, and are now replaced by alluvial plains through which streams and rivers meander. In large lakes deposits are taking place similar in all respects, save in the absence of marine organisms, to those which are being laid down in estuaries. In the smaller lakes, however, there are necessarily more rapid changes in the character of the sediment. This is the case especially with lakes which are being silted up by torrents and streams flowing with different velocities and bearing along different kinds of material. The fan-shaped accumulations formed opposite their mouths by those several streams and torrents eventually overlap and become dovetailed—so that sediments of various kinds may occur on one and the same horizon. The organic remains entombed in such sediments will consist of course of fresh-water forms commingled with relics of the land-fauna and flora. In some lakes large accumulations of shell-marl are formed, and in others deposits of iron ore take place. During dry seasons, when the surface of a

lake is lowered, mud-flats may be exposed, and come to show foot-prints, worm-tracks, rain-pits, sun-cracks, and other superficial markings, which may be preserved by subsequent deposition of sediment. Vegetation may also encroach upon the bed of a lake when its waters are low, and subsequently become submerged and buried under sand and mud. In these and other respects fresh-water lacustrine strata will often closely resemble the accumulations of a maritime delta.

When a river enters a lake it is compelled to part with its sediment, and hence the water that issues from the lower end of the lake is generally clear and pure. It is thus deprived in large measure of its eroding power. Nevertheless, some erosion takes place, and in countries where the winters are more or less severe, this erosion is greatly intensified by the action of frost. The rocks are split up along the lines of joints and fissures, and their shattered fragments are swept along by the river, so that eventually the point of outlet is lowered, and the level of the lake gradually falls. Thus partly by such "tapping," and partly by the continued increase of deltas, lakes tend to become obliterated and replaced by sheets of alluvium. Hence, we may infer that none of the existing lakes of the globe can be of very great geological antiquity, for at the present rate of erosion and sedimentation they must long ago have disappeared.

2. Salt Lakes.—Two kinds of salt lakes are recognised, viz. (*a*) *portions of the sea cut off from the general oceanic area by epigene or hypogene agencies;* and (*b*) *lakes, originally fresh-water which have been rendered saline by evaporation and concentration.* The salt lakes of the first group range in size from mere small pools up to great inland seas. Occasionally the sea during a storm breaks through or overrides the sand-banks that often fringe a low shore, and forms shallow lagoons of a more or less temporary character. Should such lagoons be protected by continued increase of the sand-banks and dunes they will gradually dry up, and a deposit of salt will be the result. But deposits of this character are of little importance. Much more extensive are the salt lakes which have been cut off from the sea by irregular movements of the earth's crust. Such appears to have been the origin of the great Aralo-Caspian depression. This wide area is believed to have formerly communicated with the Black Sea by the Ponto-Caspian depression, subsequent elevation of the land having closed that connection. A large portion of the depressed surface, which extends from the sea of Azov east through the desert plains of Turkestan to Lake Balkash, is covered with sand and clay in which shells of recent marine molluscs occur. Altogether, some 2000 salt lakes are scattered

over the immense plains, and these and the larger inland seas are all evidently drying up.

Salt lakes of the second group, which may be shortly defined as lakes which have no outlet to the ocean, are well represented by the Great Salt Lake of Utah. That the water of this lake was formerly fresh, and of much greater extent, is proved by the occurrence at various levels on the slopes of the adjoining mountains of lacustrine terraces or beaches charged with fresh-water organisms. The highest of those beaches is 1000 feet above the present surface of the lake: when the water stood at that height it covered an area nearly 25,000 square miles in extent, and drained northward into the Pacific Ocean. The saltness of the present lake is simply due to the gradual evaporation of the water, and consequent concentration of its salts. The Dead Sea is another good example of a lake which has been rendered saline by evaporation and concentration. Successive terraces rise high above its present surface, showing that it formerly covered a much wider area, and it is supposed that the Jordan formerly flowed out of that larger lake along the now dry Waddy el Arabah, and emptied itself into the Gulf of Akabah, one of the heads of the Red Sea. Earth-movements have affected the whole area: the land lying between the Dead Sea and the Gulf of Akabah having been elevated, while the basin of the Dead Sea has been depressed to such an extent that the surface of the water is 1286 feet below that of the Mediterranean. It is evident that any fresh-water lake would eventually become saline were its outlet to the ocean closed. The rainfall might be sufficiently great to counterbalance evaporation and retain the lake at its level, but the salts brought down in solution by the various feeders would continue to increase until eventually the waters of the lake became saline. In the cases of the Great Salt Lake and the Dead Sea, the processes of evaporation and concentration have been intensified by a diminished rainfall and a consequent lowering of the level.

The deposits formed in salt lakes differ in several respects from those which accumulate in fresh-water basins. The mechanical sediments are of much the same character, and are laid down in much the same way. Commingled with these, however, will be sheets of salt (sodium chloride) and layers of gypsum (calcium sulphate), dolomite (double calcium and magnesium sulphate), and other chemical compounds. The mud which forms over the bed of the lake will be more or less saturated with salts, but such saline muds will frequently dovetail with, and be overlapped by, silt, sand, and gravel, washed down by torrents and streams, especially in the rainy season. Rock-salt and gypsum are not necessarily precipitated over the whole bed of a salt lake. In the Caspian, for example,

no such precipitations can be taking place in the northern part which is freshened by the influx of the Volga. It will only be in broad shallow bays, like that of Karaboghaz, which is cut off from the open water by a large sand-bank, that widespread and more or less continuous precipitations of salt are likely to occur. Karaboghaz Bay is a kind of natural salt pan in which the waste caused by rapid evaporation is constantly made good by a stream of salt water pouring into it through a breach in the sand-bank that separates it from the main body of the Caspian. Should these conditions persist for any time the whole bay will eventually be filled up with deposits of rock-salt and gypsum.

As salt lakes are usually deficient in life, the deposits forming in them will contain comparatively few organic remains, and these will be often deformed or stunted in growth, from the unfavourable conditions under which the creatures lived. But land-plants and relics of terrestrial animals will now and again be carried down by the streams and rivers, and become entombed in mechanical and chemical accumulations. Footprints, rain-pits, sun-cracks, and occasionally old land-surfaces may also occur among the sediments of salt lakes.

Beaches.—Certain phenomena common to fresh-water and saline lakes may be briefly referred to. Along the coasts of some lakes wave-action causes considerable erosion. But this takes place chiefly in the larger sheets of water where it is possible for the wind to raise considerable waves. The waves driven ashore batter and undermine cliffs by means of the stones and gravel which they hurl along, or they rush forward over low-lying ground, tearing up the soils and subsoils, and rearranging the materials partly above and partly below the level of the lake. But such action is of little importance in the smaller lakes. Round the edge of all lakes a beach is formed by the action of the waves, and by rains, frost, etc. Rain washes down the looser materials which come to rest along the margin of the water; and frost tends to accumulate angular débris at the foot of the cliffs and steep banks which girdle many lakes. Sometimes such detritus becomes more or less waterworn and rounded; but, as a rule, lacustrine beach-deposits consist chiefly of earthy materials commingled with angular and subangular stones. It is only where there is sufficient wave-action that those materials are winnowed, sifted, and rolled so as to simulate sea-shore accumulations of gravel and sand.

CHAPTER VI.

GEOLOGICAL ACTION OF ICE.

Frost—Ice of lakes and rivers; anchor-ice; surface-ice—Hail—Snow—Glaciers; transport of rock-débris on surface of; within and underneath; giants' kettles—Sediment in glacial rivers—*Moraine profonde*—Erosion of glacier's bed—Glacial lakes—Ice in the sea; icebergs; ice-foot of Arctic regions; floe-ice.

1. Frost.—As water expands in freezing it becomes a powerful disintegrator of rocks. We have already learned that rocks are usually jointed and fissured, and that no rock is so close-grained as not to permit of the entrance of water. In all regions subject to frost, therefore, disintegration is more or less rapidly effected. The water freezing in the interstices and pores of soils, and the superficial portions of rocks, forces the grains and particles asunder, and when thaw ensues the loosened material is ready to be carried away by wind, rain, and melting snow. The same process takes place upon a larger scale in the opening of joints and fissures, and the rending asunder of rocks and rock-masses. Hence, in Arctic regions, and at high levels in temperate and southern latitudes, the wholesale shattering of rocks has produced immense accumulations of angular débris. To such an extent has this action taken place, that in some countries the rocks are more or less completely buried in their own ruins. By and by, so great does this accumulation become that the frost is unable to get at the living rock; the loose fragments, however, under which it lies concealed are themselves shattered and crumbled and pulverised, until they are ready to be swept away by wind, rain, and melting snow. By this means the solid rock again comes within reach of the action of frost, and so the process of disruption and disintegration continues. The great taluses of angular débris which cloak the slopes of our mountains, and gather thickly along the base of precipice and cliff, have been dislodged by frost and rolled down from above: their downward progress being often aided by torrents and other superficial agents. It has already been shown that frost has had a large share in the

excavation and widening of river-valleys. Much of the débris formed by the action of this powerful agent is carried away by streams and rivers, or more rapidly by floating-ice, so that we cannot estimate the amount of work performed by frost by taking into account only the masses of rock and sheets of rock-rubbish that are left lying amongst our hills and mountains.

2. Ice of Lakes and Rivers.—Quantities of frost-riven débris showered down from cliffs often accumulate upon the margin of an ice-covered lake, and much of this when the ice breaks up is carried away on floes and rafts into rivers, and may sometimes descend to the sea. Occasionally violent storms drive the ice upon the lake-shore and cause considerable destruction and confusion of beach-deposits.

In rivers, the formation of what is known as *ground-* or *anchor-ice* sometimes takes place. This kind of ice only begins to form when the temperature of the atmosphere falls to within 10° F., and it does not adhere strongly to the bottom until zero is reached. It is somewhat porous or tubular and sponge-like, and when it rises to the surface it often brings with it the stones and boulders upon which it formed. In high latitudes it is one of the most important stone-carriers, and even in the rivers of Scotland it occasionally performs this function. This was well seen in the river Tay, at Perth, during the severe winters of 1880 and 1881. The surface-ice of rivers is also an important geological agent. Stones and boulders frozen into it together with angular débris shed upon it by frost from cliffs and steep slopes are often transported in large quantities, and distributed along the river-shore or carried down to sea. Ice-rafts grating along the margins of such a river as the St. Lawrence are said to have smoothed and polished the rocks in many places. But it is probable that those rocks were more or less rounded and smoothed by glacial action (see p. 60), before the river-ice began to rub against them.

Sediments accumulating in an estuary, or upon the sea-bottom

Fig. 18.—ERRATICS IN AQUEOUS SEDIMENTARY DEPOSITS.

opposite the mouth of a river in which drift-ice abounds, will contain, scattered through them, stones and rock-fragments. Should these *erratics* or wandered blocks fall upon soft mud or silt they

will indent the sediment to a greater or less extent according to their shape, size, and weight. A sharp-pointed stone, should it fall "end on" will pierce deeper than a flatter-shaped mass which may chance to fall upon its broader face; and large and heavy stones will sink farther into the mud than smaller and relatively lighter ones. Subsequently-deposited layers of sediment will afterwards gradually bury the stones, and should the accumulations ever be exposed to the light of day, they will show such an arrangement as is seen in the annexed diagram (fig. 18).

3. **Hail.**—Although its destructive action on animal and vegetable life is not infrequently severe, hail is of comparatively slight importance as an agent of geological change. Occasionally we hear of men, beasts, and birds being killed, of trees overthrown, and of roofs of houses knocked in. Such violent action, however, is exceptional, and hail-storms seldom affect a very large area.

4. **Snow.**—The general conservative influence of snow is well known. It not only prevents the radiation of heat from the ground but protects a land-surface from the effects of severe frost. It is, however, as a destructive agent that snow appeals most to the geologist. In forest-regions the accumulation of snow upon the trees often brings them down. By repeated thawings and regelations the branches and boughs are gradually loaded with ice and snow, and, becoming top-heavy, the trees are liable to fall, even when no wind is blowing. Should one be overthrown it collides against its neighbour, and this in turn falls upon another, until shortly the trees are seen crashing to the ground in all directions. This is what is known in North America as an *ice-storm*. In mountain-regions vast accumulations of snow, becoming suddenly loosened, rush madly down the steep slopes and precipices, gathering momentum and power as they go, and sweeping stones, blocks, and débris along with them. Such falls are termed *avalanches*. The rapid melting of snow in spring is often the cause of great floods. During such floods the rivers are generally more turbid than when they are swollen merely by heavy rains. When thaw ensues the loose soils and subsoils are rendered soft and spongy, and they become more or less saturated by the water of the melting snows. To such a degree is this soaking sometimes carried that the whole surface of sloping fields is set in motion. The soil creeps, slides, and occasionally flows downwards. When the thaw is accompanied by heavy rain, as is often the case, enormous quantities of sediment are washed into the rills and brooks, and streams and rivers roll seawards laden with mud. After floods of this kind have subsided, and the waters have disappeared from the wide alluvial plains, these are found covered in many places with a more

or less thick coating of mud, loam, or silt, interspersed through which snail-shells often occur.

In some of the higher valleys of the Rocky Mountains enormous masses of rock-rubbish are accumulated. During winter these are buried under thick snow, which melts in spring, so that by and by the earthy débris becomes soaked and saturated with water, and begins to flow slowly down the valleys, forming what are called *earth-glaciers*.

5. Glaciers.—Above a certain level, which varies with the latitude and physical conditions, more snow falls than is melted or evaporated. This level is called the *snow-line*. Under the equator and in tropical regions it rises to a great height, and falls to lower elevations as it passes south and north towards polar regions, until it reaches the seashore. In the Karakorum, South Thibet, the snow-line rises to 19,400 feet above the sea; on Paachata, in the Western Cordillera of Bolivia, it reaches as high as 20,079 feet. It falls to a height of 8880 feet in the Alps, to 5500 feet in Norway, to 3835 feet in Lapland, to 500 feet in Bear Island, and to the sea-level at the south-west point of Spitzbergen. Of the snow which falls above the snow-line a portion is melted and disappears down the slopes of the mountains, and another portion is evaporated. But the supply exceeds the waste, and accumulation might go on to an indefinite extent were it not for those wonderful ice-rivers or glaciers which gradually drain the mountains of their superfluous loads of snow. When the snow has gathered to a sufficient depth its own weight suffices to press down its lower portions and to convert them into ice. The passage into ice is simultaneously carried on by alternate freezing and thawing. Drops of water released at the surface trickle downwards, and congeal again round the snow crystals below, so that by and by the snow becomes granular; and this process being repeated with each year's accumulation, the whole tends to pass into the granular condition, or, as this kind of snow is called, *névé* or *firn*. The beds of snow formed during successive winters are of very irregular thickness, each being usually marked off by a dirt-line or crust formed of a mixture of dust, small grit, and sometimes remains of insects. Thus when the whole mass of névé passes into solid ice it often shows a stratified or bedded arrangement.

For the accumulation of snow and the formation of névé and glacier-ice a certain kind of mountain-form is requisite. On steep-sided conical mountains the snow cannot collect and gather in sufficient quantity, while strong winds prevent its accumulation upon flat-topped mountains. But most great ranges and groups of mountains show at the heads of their valleys deep basin-shaped

Fig. 10.—IDEAL SECTION OF A SWISS GLACIER SHOWING MORAINES, CREVASSES, AND THE UNDULATING FORM OF THE GROUND UNDERNEATH (small roches moutonnées). (R.)

cirques and corries, the sides of which sweep up to the summit crests. This is especially the case with granitic mountains. It is in those great excavated basins that the snows deepen year after year—they are the reservoirs which supply the glaciers. From their lower ends the newly-formed ice is squeezed out by the pressure of the overlying névé, and begins to flow with a quasi-viscous motion. Streams of ice coming in this way from adjoining basins eventually coalesce and make their way into the valley below as a glacier.

Throughout its course a glacier behaves in many respects like a river—broadening out in the more open parts of its valley, and forming a narrower stream where the valley contracts. Like a river it also flows with a differential motion—moving faster at the surface and in the middle than at the bottom and sides, where it is retarded by friction.

The rate of motion depends partly upon the volume of the ice, partly upon the slope of its bed, and partly upon the season. Other things being equal a massive glacier will move faster than one which is not so large ;

and in the case of glaciers of similar size those which have the steepest course will also have the quickest motion ; while in all cases glaciers advance more quickly in spring and summer than in winter. The angle of slope in existing glacier-valleys varies from less than 3° up to 30° or more ; but with such a slope as 30° the ice is a mere silent cataract of fragments. An inclination of 8° or 9° indeed suffices to produce a jumbled and tumbled surface. Many glaciers do not flow at a greater rate than 10 or 12 inches a day, while some have been known to advance 52 inches in twenty-four hours. The glacier of Jakobshavn (Greenland) moves at the rate of 48 feet to 65 feet in the twenty-four hours. The differential motion of the ice and the irregularities of the surface over which it flows cause unequal tension, to which the glacier yields by fracturing. This is the origin of the gaping fissures (*crevasses*) by which glaciers are traversed in various directions. As the ice flows on its way such crevasses are continually closing up and new ones forming. Here and there a glacier is penetrated by more or less vertical pipes or funnels formed by the descent of water from the melting surface of the ice into a crevasse. The water soon licks out for itself on the line of the crevasse a more or less circular hollow, down which it rushes to the bed of the glacier. Such a *moulin* (mill), as it is called, gradually moving onward with the advancing ice, is by and by abandoned by the water, and a new crevasse forms in the same spot as the first, where upon the water proceeds to drill there another vertical pipe, which in like manner is deserted for a third, and so on.

The thickness of the ice in Alpine glaciers varies from 100 feet or so up to 600 feet or more ; some measurements made in moulins have given thicknesses of as much as 1000 or 1500 feet, but these are not reliable.

The distance to which a glacier flows is determined by the amount of snowfall, and by the temperature of the region into which it advances. In the Alps the ice-streams descend from 4000 to 5000 feet below the limits of perennial snow, but at their terminations they are still some 3000 or 4000 feet above the level of the sea. In Arctic regions they descend to the sea and push forward over its floor.

The surface of a glacier during day, and especially in summer, is washed by numerous rills running in all directions, the water from which, descending by crevasse and moulin, reaches the bottom, where it swells the stream or streams that flow on underneath. Much water derived from melting snow and torrents also makes its way under the glacier from the flanks of the valley, and the subglacial streams may sometimes be fed by subterranean springs.

Again, some melting goes on in the body of the ice, and heat derived from the rocks, from the water that seeks its way under the ice, and from the friction produced by the glacier upon its bed, tends to increase the amount of sub-glacial drainage. All this water collecting upon its bed by and by issues from an ice-cave at the lower end of a glacier as a full-born river.

Transport of Rock-Débris on Surface of Glaciers.—We

Fig. 20.—view of an alpine glacier.

have seen that in all elevated regions which are subject to extreme cold the action of frost produces much angular débris. The lofty precipices and steep slopes which bound most glaciers are constantly subject to this action, and rock-fragments are thus continually descending and accumulating upon the surface of the ice. So great is the supply of material that some glaciers throughout a considerable part of their course are completely buried, and occasionally as in the Himalaya the débris supports a growth of scrub and small trees.

In most cases, however, the ice-streams are too broad to be so overlaid, and the rock-rubbish, loosened by frost, or swept down by avalanches, gathers along their margins, forming linear ridges or heaps, which are called *lateral moraines.* When two or more glaciers coalesce to form one large trunk-glacier some of the lateral moraines necessarily become *medial moraines* in the conjoint ice-stream. As the ice flows on its way it carries its moraines with it down to

Fig. 21.—VIEW OF A GLACIER, SHOWING SUPERFICIAL MORAINES AND CREVASSES. (R.)

where it terminates, and there the débris, shot over the ice-front, accumulates as *frontal* or *terminal moraines.* Owing to various causes glaciers sometimes advance farther than usual, and sometimes they gradually retreat—both advancing and retreating movements being occasionally interrupted by pauses of longer or shorter duration.[1] During an advance the terminal moraines are of course pushed forward. Then should the glacier-front retreat continu-

[1] It must not be supposed that the ice *moves* backward. The apparent retreat is due simply to the ice being melted away more rapidly than the glacier advances; the waste, for the time being, exceeds the supply. This may arise, for example, from a long succession of dry seasons, during which the snow reservoirs become depleted.

ously for some distance its morainic material will be strewed over the bed of the valley as an irregular sheet. Should a pause in the retreat now supervene a new line of moraine-mounds will begin to accumulate farther up the valley, and these will be large or small according to the length of time the glacier is able to maintain its front in the new position. Thus in some glacier-valleys we may find several successive lines of frontal moraines marking pauses in the retrogression of the ice. As the end of a glacier is usually convex in form or tongue-like, the rubbish shed from the surface accumulates in ridges and mounds of a horse-shoe shape, the concave side facing, of course, up the valley. The action of the water escaping from a glacier often interferes with the accumulation of the moraines, washing the material away and spreading it in broad sheets over the valley. In the case of some narrow glaciers nearly all the morainic matter is thus disposed of.

While the lateral and medial moraines consist almost exclusively of angular débris, terminal moraines not infrequently contain a certain admixture of water-worn materials, which are apt to be more abundant in the case of large than small glaciers. The rounded stones are derived partly from the stream that issues at the end of a glacier, and partly from runnels that wash the surface of the ice, rolling along stones and grit which have come from the superficial moraines.

Transport of Rock-Débris enclosed in Glaciers.—Superficial moraines now and again are engulphed in crevasses, and, after travelling for some distance down the valley in this position, they reappear at the surface. This is due to the ablation or melting of the ice, and to the curving upwards of the lines of flow in the glacier. It is probable also, as Forbes maintained, that stones are introduced into the ice by friction at the bottom of the glacier, and gradually forced upwards to the surface in the same way by the action of the frontal resistance. Mere melting and evaporation will not explain the reappearance at the surface of blocks and rubbish which have fallen into crevasses. The ice is kept at its general level not by the accumulation of snow upon its surface, but by the new supplies which are continually pouring into the valley at its origin. In other words, the ice in front rises just as fast as the ice advances from behind: it is thus that the general thickness of the glacier is maintained. If this were not the case the stones falling into a crevasse for, say, 100 feet from the surface, would always remain embedded in the ice, occupying the same relative position until they were ejected at the terminal front. Rock-fragments travelling in the ice are not abraded. This is well shown by the fact that knapsacks and other perishable objects, after having been

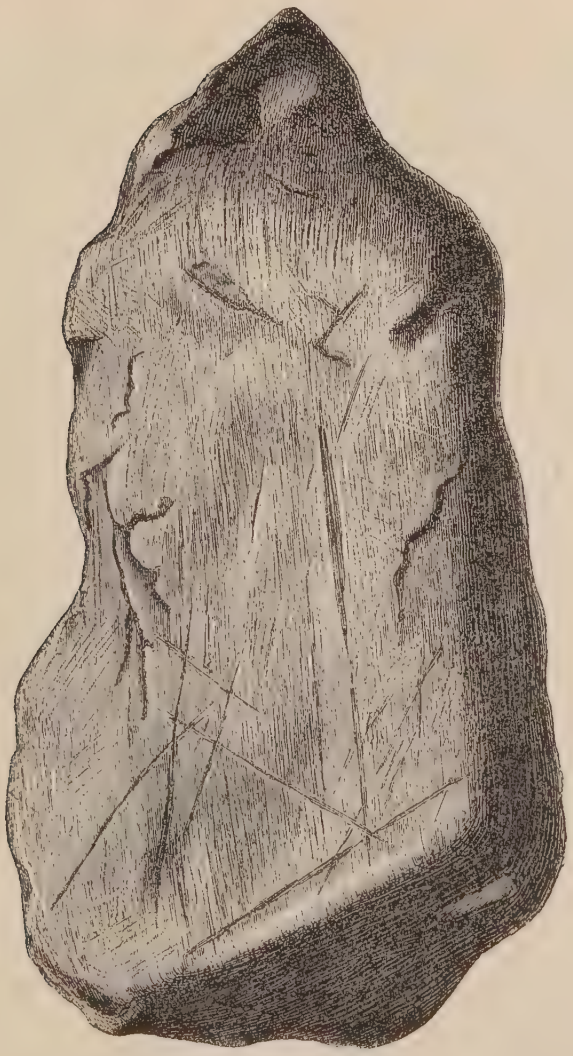


Fig. 22.—ICE-SCRATCHED STONE.

engulphed for years, have been again disgorged. In 1860 a well-preserved corpse, clad in a costume which had been abandoned for

centuries by the mountaineers, was thrown out by the Ahrenthal glacier.

Transport of Rock-Débris underneath Glaciers.—Angular débris must frequently be introduced to the bottom of glaciers by profound crevasses, and much also is carried underneath the ice, especially in the warmer seasons, by torrents and melting snows, descending the steep sides of the valleys. Rock-fragments are also torn and wrenched by a glacier from the bed over which it advances. Such fragments frozen into the ice are grated over the rocky pavement, and doubtless help to dislodge similar fragments. Partly held in the ice, and partly dragged and rolled forward upon themselves, the angular stones are rubbed, scratched, and smoothed, while their sharp edges and corners get blunted. All this grinding and rubbing results in the formation of grit, sand, and very finely divided clay, which aid in the scratching and polishing of the stones. These stones, it is to be noted, are most prominently striated in the direction of their longer diameter—that is, lengthways. This is because, while being dragged forwards, they arrange themselves in the line of least resistance. Now and again, however, they are rolled over and get rubbed and scratched in other directions. Round flat stones, and stones which are as broad as they are long, owing to their shape, are scratched equally well in all directions. The débris thus modified by glacial action is subject to the wash of sub-glacial waters, which sift and winnow the sand and clay, and roll the stones forward, so that many of these become water-worn and rounded. Hence considerable quantities of gravel and finer sediment are continually being swept out from underneath the glacier at its terminal front. The water that descends to the bottom of the ice by moulins, we can hardly doubt, must bring about the formation of pot-holes of large size, by setting stones and boulders in rapid rotation. Such great pot-holes, or *giants' kettles* as they are termed, have often been observed in the deserted beds of glaciers, and can hardly have had any other origin, since they are usually charged with well-rounded boulders and other water-worn materials.

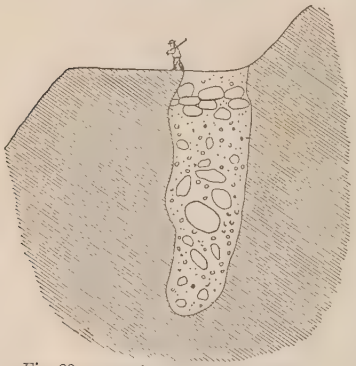


Fig. 23.—Giant's Kettle: filled with boulders, gravel, etc.

All glacial rivers are more or less muddy, and there cannot be the slightest doubt that the fine sediment which they carry in suspension has been derived from the grinding action of the glacier on its detritus, and the rocky pavement over which that detritus is dragged and rolled. Some faint idea of the amount of this glacial erosion may be gained by such estimates as have been made of the quantity of fine sediment carried in suspension by glacial rivers at their point of issue from the ice. The average

Fig. 24.—ROCHE MOUTONNÉE WITH PERCHED BLOCKS, PONT-Y-CROMLECH, PASS OF LLANBERIS. (R.)

daily discharge of the river that issues from the Aar glacier in summer is about 440 millions of gallons, in which are contained, according to MM. Dolfuss and Desor, some 280 tons of fine sediment. And yet this estimate takes no account of the coarser detritus which the river pushes along its bed. Again, it has been estimated by Helland that the amount of sediment carried out from the Justedal glacier (Norway) represents a loss of 69,000 cubic metres of rock every year, which is equal to a cubic mass measur-

ing 41 metres on the side. In some of the glacial rivers of Greenland the sediment is greatly in excess of that amount.

The stones, clay, etc., which gather and are pushed forward under a glacier, are called the *ground-moraine, bottom-moraine, moraine profonde,* or *moraine de fond.* This moraine in the case of Alpine glaciers is probably of a very patchy character, and nowhere very thick. We may infer this from the general steep inclination of the valleys which causes a comparatively rapid motion of the ice, so that morainic matter cannot possibly collect to any extent. Moreover, owing to the action of the sub-glacial waters, a considerable portion of the débris is washed away. Where this débris is unmodified by water it is a rude pell-mell agglomeration of grit, sand, and clay, packed with angular, sub-angular, and smoothed and striated stones of all shapes and sizes.

Erosion of the beds of Glaciers.— The constant grinding of a glacier tends to remove asperities and irregularities in its bed. Only give it sufficient time and the ice will eventually remove all projecting bosses and knobs of rock, and provide itself with an equal and smooth channel. Its efforts to reduce the inequalities of its bed are seen in the phenomena of *roches moutonnées* or rounded rock-surfaces. These roches moutonnées have generally a smooth and a rough side—the former of which looks up-stream and the latter in the opposite direction. Sometimes they are smoothed and polished all over, but when this is the case they do not rise prominently above the general surface of the ground. Every gradation, in fact, may be traced from conspicuous individual roches moutonnées (each with its smoothed or *stoss-seite* and its rough non-glaciated side or *lee-seite*) to low gentle undulations and approximately flat surfaces which are polished and striated all over. The striæ imprinted upon the bed of a glacier point down the valley, but occasionally they are deflected to right or left as the case may be. These deflections are well seen upon the roches moutonnées which have been left exposed upon the beds of extinct glaciers. It is evident that although buried in ice such projecting rocks must divide the current that flows against and over them. Glacier-ice being a plastic body, accommodates itself to the irregularities of its channel, much in the same way as a stream that makes its way over submerged reefs and boulders.

Although the general tendency of a glacier is to bevel off and remove all excrescences in its path so as to provide for itself an equally graded way, yet the conformation of the ground often compels it to excavate hollows below the general surface upon which it advances. This action takes place in front of very prominent obstructions. An abrupt hill or crag, surrounded and overwhelmed

by a glacier, by opposing the advance of the ice induces excessive erosion upon the ground immediately in front of it. The ice pressing against the rock is forced down upon the bed of the glacier by the ice continually advancing from behind, and ere long a hollow is scooped out in front of the crag. This hollow is continued along either side of the obstruction, but generally shallows off as the ice sweeps round the crag and escapes pressure and strangulation. The clay, grit, and rock-fragments which it drags along at the same time tend to collect behind the crag, where of course little or no glacial abrasion can take place. This is the appearance known as *crag and tail* (fig. 25). Similar phenomena may be seen in the bed

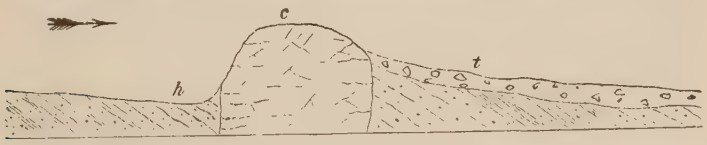


Fig. 25.—CRAG AND TAIL.

c, Crag; *h*, hollow scooped out in front of crag; *t*, tail of glacial detritus.

of a stream, where we observe hollows being eroded in front of large boulders and long banks of gravel and sand gathering in the quiet water behind.

Speaking generally, we may say that glacial erosion tends to convert the V-shaped valleys, which are the work of rivers and their allies—springs, frosts, etc.—into more or less flat-bottomed or U-shaped valleys (fig. 26).

GLACIER LAKES.—Occasionally a glacier advancing across the

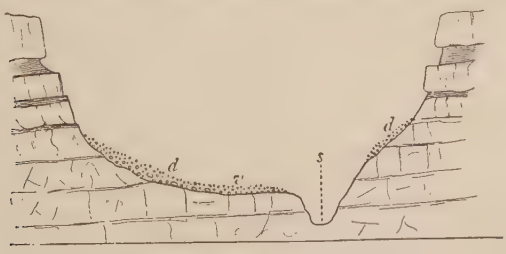


Fig. 26.—SECTION ACROSS A U-SHAPED VALLEY.

v, Bottom of glaciated valley; *s*, V-shaped valley cut by river; *d*, debris.

mouth of a lateral valley, in which a stream is flowing, may dam the water back and form a lake. And the same result will follow when a glacier, coming from a lateral valley, invades and crosses a main valley in which there is a river. Such lakes may exist for a

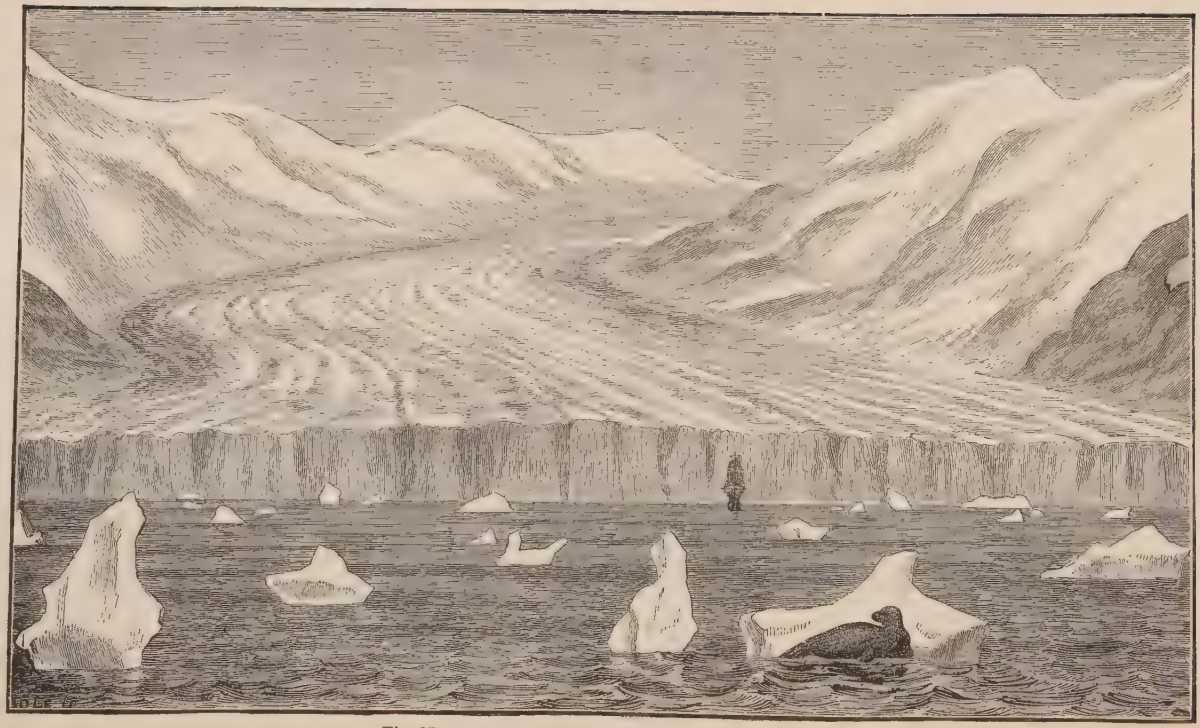


Fig. 27.—VIEW OF ARCTIC GLACIER ENTERING THE SEA.

long time and form receptacles in which sediment will accumulate. As the barrier is removed by degrees, or by fits and starts, the lake-level will be lowered, and a succession of lacustrine beaches will be formed upon the valley-slopes. The sudden rupturing of such ice-dams, as already shown, has caused very destructive floods.

6. Ice in the Sea—ICEBERGS.—In high northern and southern latitudes glaciers enter the sea, and flow outwards until the superior density of the sea-water overcomes the tenacity of the ice, and forces off larger or smaller segments which float away as *icebergs*. Opposite such glaciers submarine moraines gather; but as the surface of Arctic glaciers like those of Greenland shows but little rock-débris—in some cases none at all—the terminal moraines of such glaciers must consist largely of the detritus washed out from

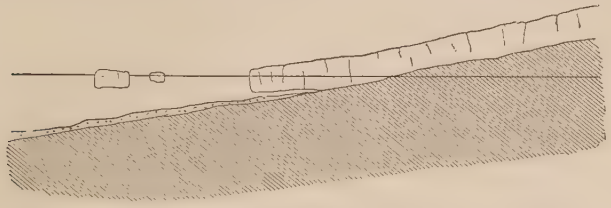


Fig. 28.—SECTION OF ARCTIC GLACIER ENTERING THE SEA AND CALVING ICEBERGS.

underneath the ice by sub-glacial waters. We can conceive, therefore, that submarine moraines will show considerable traces of water-action, and that owing to the mode of their accumulation they will be more or less stratified. As examples of submarine, terminal, or frontal moraines, may be mentioned the Tallert Bank, in front of the glacier of Eisblink, and the broad bank opposite the glacier of Edge Island (Spitzbergen).

The whole interior of Greenland appears to be one enormous ice-field, above the surface of which rocks seldom or never appear. From this vast reservoir of ice, extensive glaciers stream outwards, following doubtless the lines of great valleys, and descend to the sea. In Southern Greenland they terminate in the deep fiords with which the coast-line is indented, while farther north they entirely fill such fiords, and even project beyond the outer coast-line into the open sea. It is only after they have entered a fiord that they become liable to have rock-débris showered upon them from above. But such débris forms only along their margins—there are no medial moraines as in Alpine glaciers. And from the great width attained by Arctic glaciers their lateral moraines appear relatively insignificant. The Humboldt glacier, for example, presents to the sea an ice-wall rising some 300 feet above its level,

and extending from Cape Forbes to Cape Agassiz, a distance of 60 miles. Hence very few of the icebergs which fall from or are forced off the ends of such glaciers can carry away relics of the land. Now and again they may contain mud and stones, which got frozen into them when they occupied the bed of a glacier, but this also must be exceptional. The only icebergs which are likely to carry stones are those which become detached from those portions of a glacier which support a lateral moraine.

Icebergs vary much in size—some of the largest ones met with in Arctic seas indicate a great thickness for the land-ice. Captain Ross mentions one lying aground in 61 fathoms of water, which measured 4169 yards long, 3689 yards broad, and 51 feet above the level of the sea. Its weight was estimated at 1,292,397,673 tons. A square-shaped iceberg seen aground by Dr. Hayes measured 315 feet high and a fraction over three quarters of a mile long. He estimated its cubical contents at 27,000 millions of feet, and its weight as about 2000 millions of tons; and since by measurements previously made he had discovered that fresh-water ice floating in salt water has above the surface to below it the proportion of one to seven, this mass must have grounded in a depth of nearly half a mile. The glaciers and icebergs of our hemisphere, however, pale before those of Antarctic regions. The whole area surrounding the South Pole is covered with an immense sheet of ice which flows out bodily on all sides into the ocean, where it terminates in a vertical wall rising 180 feet above the sea-level. From this great wall large flat-topped tabular masses are detached and float away as icebergs, some of which have been found by angular and reliable measurements to be 600 or 800 feet high and several miles in circumference; others still higher have been reported. Thus the ship *Agneta* passed one in lat. 53° 14′ S., long. 14° 41′ E., which was 960 feet in height. Allowing that only a seventh part[1] of a square-shaped iceberg appears above the surface, it is evident that some of the Antarctic icebergs must exceed a mile in thickness.

As icebergs float deeply they come under the influence of oceanic currents, and in spite of contrary winds may drift for vast distances, so that any stones they contain may be carried sometimes for thousands of miles, and drop eventually to the bottom of the sea amongst the finest oceanic sediments. When icebergs run aground they will push up and throw into confusion any deposits which may be gathering there; or should they go ashore upon bare rocks, they may crush, shatter, and displace these.

Ice-foot of Arctic Regions.—Along the coast of Greenland

[1] Some make it an eighth part.

from near the Arctic Circle up to Kennedy's Channel a narrow shelf or platform of ice, varying from 60 to 150 feet in breadth and up to 30 feet in thickness, adheres to the rocks, accommodating itself to every sweep and indentation of the coast-line. In the higher latitudes this shelf, which is formed by direct freezing of the sea, never entirely disappears; but farther south it breaks up and vanishes towards the end of summer. This shelf is called the *ice-foot*. During summer great piles of rock-rubbish, showered from the cliffs above, crowd its surface. When, as frequently happens, portions of this ice-belt are forced away from the land by the violent impact of massive floes, currents carry southward the rock-

Fig. 29.—ICE-FOOT OF THE ARCTIC REGIONS.

laden fragments which ere long melt away and drop their burden. The quantities of rock-débris thus borne seawards must be enormous, and greatly in excess of the material transported by icebergs.

FLOE-ICE.—The ice that forms on the surface of the open sea rarely attains a greater thickness than 18 or 20 feet. In summer time it breaks up and is carried along as *floe-ice* by currents, and often driven ashore in large quantities. When it "packs" on shore in this way it disturbs beach-deposits, pushing these above high-water mark, while it crushes and shatters rock-surfaces, and may scratch these irregularly with the gravel and grit which it drives forward.

CHAPTER VII.

GEOLOGICAL ACTION OF ICE—*continued.*

Former great extension of ice-action—Ice-action in the Alps and in Arctic and Antarctic regions contrasted—Evidence of former glacial action in temperate latitudes—Character of stony clays or ground-moraines of low grounds of Switzerland and Italy—Ground moraines in other parts of Europe—Period of wide-spread glaciation—Origin of glacial lakes—Lake of Geneva—Fiord-basins and deflection-basins.

7. Former Greater Extension of Ice-Action.—Our knowledge of the mode in which ice does its work has been greatly increased by a study of the relics of glaciation which occur in many regions now far beyond the reach of glacial action. Hitherto we have restricted our attention to the work being done by geological agents in our own day, and we have not stopped to consider how this work, so far as it is known to us, helps us to explain geological phenomena. Nor is it necessary to do so in the case of such agents as the atmosphere, rain, frost, and terrestrial waters. The action of all these agents of change is sufficiently open to inspection and observation. We can follow running water, for example, from its source in the mountains down to the sea; we can watch the gradual process of erosion and deposition in all its details; nor can we have any doubt that this process must have been the same in all ages, ever since rain began to fall and rivers to flow. But a little consideration will show that in the case of ice-action we are at some disadvantage. We can study what is going on in the glacier-valleys of the Alps; we can have no doubt as to the manner in which rock-rubbish is transported on the back of a glacier; and we can assure ourselves as to the character of glacial erosion. Could we conjure those glaciers away we can tell exactly what kind of relics would be left behind. We should find perched blocks and lateral and terminal moraines marking out the vertical and horizontal extension of the vanished ice-streams; and their deserted beds we should expect to see rubbed, smoothed, and striated, and diversified probably with roches moutonnées, and crag and tail.

Giants' kettles might occur here and there; and the bottom of the valley would be sparsely sprinkled with glaciated, partially glaciated, and rough angular stones, with patches and sheets of gravel, grit, sand, and clay. Here and there, sheltered behind prominent knobs of rock, such materials might occur in considerable quantities. But as a rule there would be little sub-glacial material of any kind. The glaciers of the Alps, however, do not tell us all that is being done by the action of land-ice. Greenland, as we have seen, and the vast regions that surround the South Pole are covered by enormous ice-sheets, which flow outwards for great distances upon the bed of the sea. Here we have the case of wide land-surfaces—no doubt consisting largely of low-lying and gently-undulating ground—completely buried under flowing ice which must reach a thickness of several thousand feet, as is shown by the size of the icebergs that are shed from the glaciers of Greenland and the vast ice-wall of the Antarctic Circle. It is extremely unlikely that the conditions of erosion and accumulation under such ice-sheets can exactly resemble what is going on in the bed of a petty Alpine glacier. Were our knowledge of river-action confined to what we may learn from the torrents of mountain-valleys, we might infer that running water was engaged chiefly in eroding, and that no deposition worth mentioning ever took place along the course of a river. And yet, as we have seen, deposition is constantly going on in the plain-track; and this plain-track is ever being increased at the expense of the more steeply-sloping valley-track and mountain-track. Now the pigmy glaciers of the Alps are simply ice-torrents, which never flow sufficiently far to enter and dilate upon the low grounds: they have neither valley- nor plain-track. They occupy the upper ends of mountain-valleys; they flow down comparatively steep gradients; they are confined within narrow channels. The action of existing Alpine glaciers, therefore, cannot reproduce for us all that is going on underneath such ice-sheets as those of Greenland and the Antarctic Circle. It would seem then, at first sight, as if our knowledge of the action of land-ice must be very limited. Alpine glaciers do not tell us enough, and the areas over which glacier-ice is most extensively developed are of course completely concealed. But if it can be shown that our Alpine glaciers were formerly of much larger size—if it can be proved that in earlier times they streamed down their mountain-valleys, and, escaping from these, spread themselves out over the low grounds—then a study of the detritus scattered over their deserted beds might be expected to throw further light on the subject of glacial erosion and accumulation. Now, abundant evidence is forthcoming to show that during a late geological period the glaciers of the Alps

had this great extension. Perched blocks, roches moutonnées and striated rocks, and terminal moraines, all conspire to prove that the mountain-valleys of Switzerland were formerly choked with ice, which covered the low grounds of that country, and streamed out upon the adjacent low-lying tracts of France, Germany, and Italy. We are therefore able to examine the deserted beds of glaciers, compared to which the largest existing valley-glaciers are the merest pigmies, and we find them covered in many places with sheets of a remarkable stony clay. This stony clay is best developed in the low-lying tracts, as in the low grounds of Switzerland, or the gently undulating areas that extend around the lower ends of most of the Italian lakes. It varies in thickness from a few feet up to 20 or 30 yards; but when it is traced up the mountain-valleys it becomes thinner and occurs in less continuous sheets, until, by and by, as we penetrate farther into the mountains, it appears only in patches, which are generally found lying in the lee of prominent knobs and crags of rock, the exposed faces of which look up the valleys. The clay itself is unstratified, that is to say, it is not arranged in separate layers and beds like ordinary river-sediment. Moreover, its contained stones are scattered confusedly through its mass without any reference to their different specific gravities or relative weight and size. These stones are of all shapes and dimensions, from mere grit up to great blocks several tons in weight. Many of them are blunted and sub-angular, and show on one or more sides that smoothed, abraded, and striated appearance which is characteristic of glacial action. They are, in short, precisely similar to the glaciated stones which one can pick out from underneath a modern glacier. The clay itself is tough and hard, and has apparently been subjected to intense pressure, as is further shown by the presence now and again of a kind of "pseudo-lamination" and "pseudo-bedding," often marked by differences of colour, and sometimes by lines of stones. These structures are evidently due to the shearing and yielding of the clay under pressure. Here and there lenticular patches and irregular nests and beds of well water-worn stones and gravel, sand and clay, occur, completely enclosed in the tumultuous stony clay, and these water-arranged deposits are often confused, contorted, and involved with the stony clay in such a way as to show that they and the latter had been rolled forward upon each other. In short, all the evidence points to this stony clay being the bottom- or ground-moraine of the ancient glaciers. It consists of the glaciated stones and boulders and detritus of grit, sand, and clay which resulted from the grinding action of land-ice, and the manner of its distribution indicates the mode in which it has been accumulated. Underneath existing

Alpine glaciers, very little bottom-moraine can be accumulated—the narrow valleys in which they flow are more or less subject, all over their beds, to the action of sub-glacial waters. Hence most of the stones are eventually swept out, and the finer sediments are carried away in suspension by glacial rivers. But when, in former times, the ice descended to lower levels and overspread wider areas, the conditions for the accumulation and preservation of a bottom-moraine became more favourable the farther the glacier advanced into the low grounds. Water, under such circumstances, could not act over the entire bed of the glacier, and consequently fine clay, sand, grit, and stones—the products of glacial erosion and abrasion—tended to accumulate. Owing to the enormous pressure exerted by the ice, this sub-glacial detritus was dragged and rolled forward *en masse*, until in places it became too thick to be so operated upon. Under such circumstances shearing-planes were formed in the stony clay itself—the upper portion being squeezed and dragged forward over the lower. The stony clay, continuing to collect, a succession of such shearing-planes were produced here and there over the bed of the glacier, and thus the bottom-moraine acquired at intervals a pseudo-bedded appearance. Owing to irregular movements of the ice, however, the thicker accumulations of bottom-moraine were more or less disturbed, torn up, and rolled forward bodily, and thus the lines of compression and shearing became confused, crumpled, contorted, and involved. The farther the sub-glacial detritus travelled under the ice the better rubbed and glaciated were the stones and boulders, and the more finely divided and compacted did the grit, sand, and clay become. Water, circulating under the glacier, formed here and there beds of gravel, sand, and finely laminated clay, but such water-channels were necessarily subject to change, and their deposits were liable to become involved with the bottom-moraine. The glacier would gradually thin away or lose in thickness as it approached its termination, and, this being so, its bottom-moraine naturally tended to accumulate more readily as the ice-mass lost weight and erosive energy.

The chief characters of bottom- or ground-moraine may be thus summarised :—

1. Unstratified clay, mixed with sand and grit, and containing large and small stones, many of which are glaciated, scattered promiscuously through it.

2. The included stones have been detached from rocks belonging to the drainage-system in which the moraine material occurs.

3. The clay is much compressed, hard and tough, and often shows shearing-planes and lines of pressure.

4. Gravel, sand, and silt or clay, arranged in beds—the result

of sub-glacial water-action—occasionally appear enclosed in the unstratified stony clay, and are frequently highly confused and involved with the latter.

5. The bottom-moraine is thickest over the low-lying and more gently-inclined ground, and thins off as it is followed up the valleys until, where these become narrow and steep, it appears only in patches, and chiefly in the rear of prominent rock-masses, that is, on the side which looks down the valleys.

6. In the lower reaches of the valleys the moraine is not only thicker, but a larger proportion of its included stones are more or less well glaciated. In the upper reaches the clay is more mixed with sand and grit, and it contains a larger proportion of angular and non-glaciated stones and rock-fragments. In other words, the farther the morainic material travelled under the ice the better rubbed and smoothed the stones became, and the greater was the accumulation of finest sediment—the "flour of rocks," as it has been termed.

Ground-moraines occur in many other regions in Europe. They are met with, indeed, in the valleys of almost every considerable hilly tract in Middle Europe, such as the mountains of Central France, the Vosges, the Black Forest, the Harz, the Erzgebirge, the Riesengebirge, the Böhmer-wald, and the Carpathians. They occur also in Southern Europe, as in the Pyrenees, the Sierra Nevada and other Spanish ranges, the mountain-valleys of Corsica, the Apuan Alps, the Apennines, the Despoto Dagh of Roumelia, the Caucasus, etc. In Northern Europe, however, they attain an enormous development. They cover vast tracts in Northern and Central Russia down to the 50th parallel of latitude. In like manner they spread over extensive areas in Poland, Saxony, Prussia, Hanover, Holland, Schleswig-Holstein, Denmark, Sweden, and Norway. They are well developed also in the British Islands, covering large portions of Scotland and Ireland, and being met with in Wales and England more or less abundantly over all the districts lying north of the Bristol Channel and the valley of the Thames. Throughout those regions these bottom-moraines are of essentially the same character as those of the Alpine lands of Switzerland and Italy, and they are constantly associated with other evidence of glacial action, such as roches moutonnées, striated rocks, and shattered and disturbed rock-surfaces. Everywhere they lie thickest on the broad plains and gently-sloping surfaces, and they always thin off and become more or less patchy as they are followed into the mountains. Thus they attain a great thickness, and spread continuously over wide areas in the plains of Northern Germany and Central Russia, in Holland, Schleswig-Holstein, Denmark, and

Southern Sweden ; but they are thinner and more interrupted in the hilly tracts of Finland and Scandinavia, being confined in such regions chiefly to the valleys. In Britain this bottom-moraine is called *boulder-clay* or *till*. It was formed and accumulated under a great ice-sheet during what is known as the Glacial Period or Ice Age, the general conditions of which will be described in chapter xxv. Thus the study of these ancient bottom-moraines enables us to form some reasonable notion of the work which is now being performed by the immense sheets of ice which are slowly grinding and abrad-

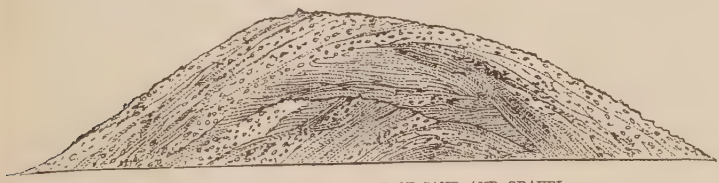


Fig. 30.—SECTION OF A KAME OF SAND AND GRAVEL.

ing such vast tracts of land within the Arctic and Antarctic Circles.

These conclusions are still further strengthened by the appearance of the terminal-moraines, and the prodigious heaps and sheets of fluvio-glacial detritus which were accumulated during the growth and final decay of the northern ice-sheet and the great glaciers. The moraines are typically represented by the mounds and ridges of boulders, shingle, gravel, and sand which circle round the lower

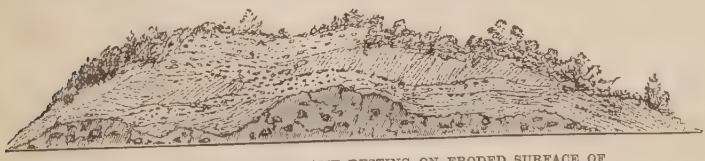


Fig. 31.—SECTION OF A KAME RESTING ON ERODED SURFACE OF BOULDER-CLAY OR TILL.

ends of the great lakes of North Italy. Similar gravelly and sandy moraines, called *kames*, exist in our own country. They are often well seen opposite the mouths of mountain-valleys, as along the foot of the Highlands in Strathmore, facing such mountain-valleys as that of the Isla. They often show diagonal bedding, as in the accompanying illustrations (figs. 30, 31). Such gravelly moraines point to the copious discharge of water from the glaciers. Occasionally, however, the gravel and sand are replaced by large boulders and earthy débris. Another set of gravel-ridges or kames appear

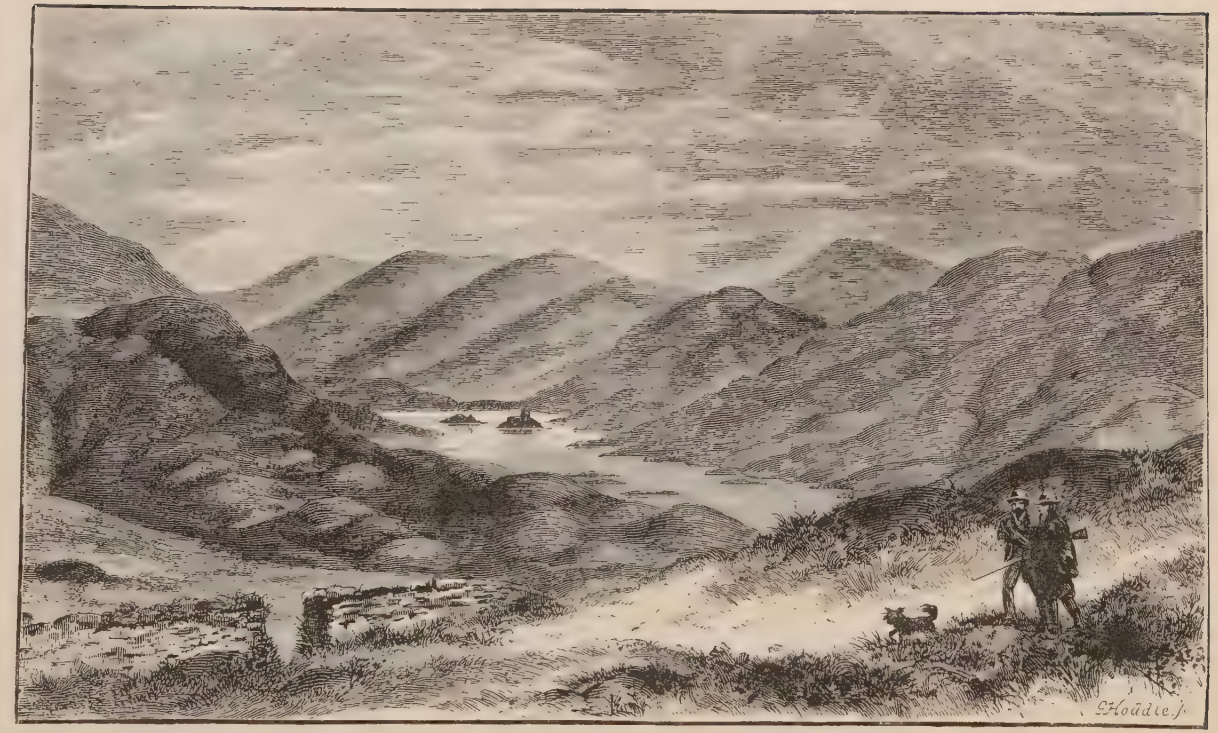


Fig. 32.—LOCH DOON (AYRSHIRE); A ROCK-BASIN. The adjacent hill-slopes are rounded by glacial action.

to have had another origin. These are long winding ridges, best developed in the Lowlands, which sometimes extend for many miles. They consist principally of gravel and shingle, and are rarely well-bedded. In Sweden they attain a great development (see *postea*, chap. xxv.) They are believed to have been formed underneath the *mer de glace*, and to mark the site of sub-glacial torrents and rivers. During the final retreat of the glaciers it sometimes happened that lakes were formed by the damming-up of valleys by glaciers. The well-known Parallel Roads of Glenroy represent the margins of such an ice-dammed lake.

8. Origin of Glacial Lakes.—When the great ice-sheet of Northern Europe had melted away, the ground was left covered with abundant irregular sheets and heaps of detritus, in the hollows of which water accumulated, forming lakes of larger and smaller dimensions. Sometimes those lakes are entirely surrounded by glacial deposits, but often they rest partly on morainic materials and partly on hard rocks. Many of the lakes whose outlet is over morainic matter have been drained by the action of the streams cutting for themselves a deep channel. Others, however, whose outlets are over hard rocks, have persisted—their streams have not yet had sufficient time to erode channels deep enough to drain off the waters. There is another large class of glacial lakes, the origin of which has given rise to much controversy. This class is typically represented by the mountain-valley lakes of Scotland, England, Ireland, Norway, and the Alps, which lie in rock-basins. According to Sir A. C. Ramsay these lakes owe their origin to the excavating action of glacier-ice. He has pointed out that in the case of great valley-glaciers erosion would be most intense where the ice was thickest, namely, somewhere in the lower course of a valley between the steeper descent of its upper reaches (where the ice is comparatively thin) and the termination of the flow. At the base of the steeper descent, where the valley begins to flatten out, the ice of a glacier tends to heap up; thereafter, as it continues to flow down its valley, it becomes gradually thinner and thinner—and pressure and erosion must of course diminish with this attenuation. Such conditions, after some time, would necessarily result in the formation of an elongated rock-basin, sloping in gently from either end, and attaining its greatest depth at some point above a line drawn across the valley midway between the upper and lower ends of the rock-hollow. The observed form and depths of rock-basins tally well with Ramsay's theory, and cannot be explained on any other hypothesis (see figs. 33, 34, 35). It is a remarkable fact, moreover, that fresh-water lakes predominate in northern and Alpine countries, while they are comparatively rare in regions

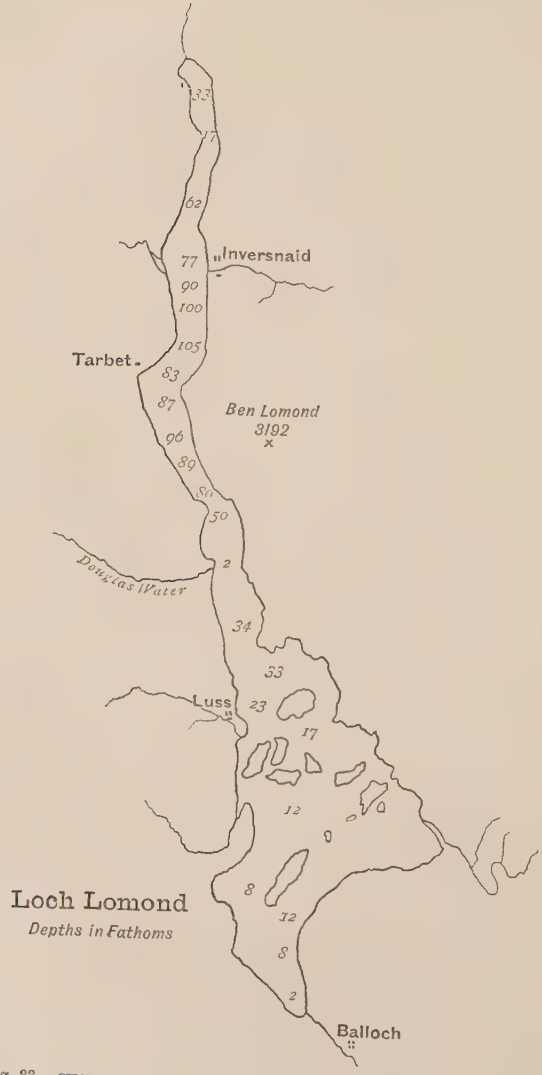


Fig. 33.—CHART OF LOCH LOMOND: A GLACIALLY-EXCAVATED ROCK-BASIN.

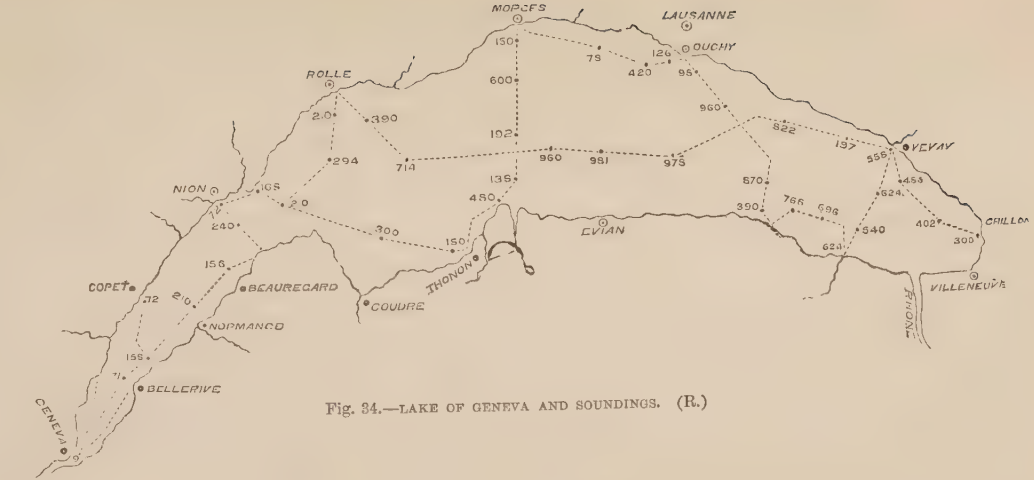


Fig. 34.—LAKE OF GENEVA AND SOUNDINGS. (R.)

Fig. 35.—OLD GLACIER OF THE RHONE COVERING WHAT IS NOW THE LAKE OF GENEVA. (R.)

The shaded part represents the rock-basin beneath the lake; the dark line the lake, showing its depths on a true scale. The light part above represents the old glacier of the Rhone. Figures, depth of the lake in feet.—*Ramsay.*

farther south and outside of mountainous districts. The great development of lakes in Finland finds no counterpart in the low grounds of southern latitudes. It is, in fact, in regions where glacial action formerly prevailed that rock-basins are most numerous. In a word, rock-basins and glaciation go hand in hand.

The Lake of Geneva has been specially cited by Ramsay as a typical rock-basin excavated by glacial action. A glance at the accompanying map will show that the lake gradually deepens from opposite the mouth of the Rhone to nearly 1000 feet between Ouchy and Evran, and thereafter shallows off towards Geneva. Now this long broad hollow occurs just where the ancient glacier of the Rhone was thickest, and where its grinding power must have been greatest. From an examination of Ramsay's section of the old glacier of the Rhone (fig. 35), which is drawn on a true scale, it is evident that the depth of the rock-basin is relatively insignificant. This is the case with all glacially excavated hollows. The depths of many of these approach and some exceed that of Lake Geneva, but when the length and breadth of such basins are kept in view we see that they are mere shallow pans. For example, the depth of the rock-basin in which Loch Lomond lies exceeds 600 feet, and yet so extensive is that lake that, were the water drained off, the unassisted eye would hardly be able to recognise the basin-shaped character of the bottom—the lake-bed would appear like a flat or plain. Ramsay supposes the basin of Lake Geneva to have been excavated by the Rhone glacier when that reached no farther than the lower end of the lake. But when the glacier attained its maximum development it flowed for many miles beyond this point, and spread itself out upon the plains of France. At that time the ice that overflowed the present site of the town of Geneva was some 3200 feet thick. Not only the basin of the lake, but all the low grounds lying between the Alps and the Jura, were deeply buried under the ice that radiated outwards from the upper valley of the Rhone. When such was the case, it is evident that the bottom of the rock-basin would be modified, especially along its northern section, by the ice which was forced out of it and compelled to move towards the Jura. We should, therefore, expect to meet with considerable depths in the northern portion of Lake Geneva, for it was just here where the ice, meeting with obstruction to its flow, would exert greatest erosive power.

Fiord-Basins.—Rock-basins, some of them of great extent, are well-known to occur in the fiords of Norway, and those similar sea-lochs that penetrate the mountainous regions of Western Scotland. All those indentations in the land are merely submerged valleys which were formerly occupied by glacier-ice. Were the north of

Fig. 36.—LOWER END OF LOCH ETIVE, A FIORD BASIN. (R.)
Water at ebb tide falls over the lip of the basin forming the Falls (Connel Ferry).

Italy to be submerged so as to allow the sea to enter the great lake-valleys, we should have a series of fiords of the same character as those of Norway and Scotland. An elevation of the sea-floor in North-west Europe, to the extent of 600 feet or thereabout, would unite the Hebrides and other islands to the mainland of Scotland, while the present fiords would be represented by wild mountain-valleys, each containing one or more lakes occupying glacially eroded hollows (fig. 36).

Deflection-Basins.—The ice-sheet that covered Scotland not only filled up the sea-lochs, but was of sufficient depth to occupy the whole basin of the Minch, and to overflow the Outer Hebrides up to a height of 1600 feet. This ice streamed outwards from the mainland in a general west by north direction, and its advance towards the Atlantic was necessarily impeded in many places by the lofty islands it encountered in its path. Hence in front of all such obstructions excessive erosion took place, and deep hollows were excavated upon the rocky floor over which the ice-sheet advanced. The detailed soundings made by the officers of our Royal Navy show that such rock-basins exist in front of all the steep rocky islands that face the direction whence the ice came, while they are entirely wanting on the lee-side of such islands. As examples may be mentioned the submarine hollow off the north-eastern coast of Rum, and the great series of similar excavations which occur upon the sea-floor along the whole extent of the Outer Hebrides. The general trend of these basins is at right angles to the direction taken by the ice that overflowed the islands, and this shows us that the lower portions of the ice-sheet which abutted upon the islands were deflected and compelled to flow along the inner margin of the obstruction as an undertow. Rock-basins excavated in this manner may be termed *deflection-basins.*

CHAPTER VIII.

GEOLOGICAL ACTION OF THE SEA.

Marine erosion—Formation of cliffs, rock-terraces, and beaches—Forms of cliff and beach in homogeneous rock-masses; in rocks of variable composition—Influence of rock-structure upon the form of cliffs—Transport and accumulation of sediment—Littoral or shore-accumulations—Infra-littoral and oceanic accumulations—Abysmal or pelagic accumulations.

As a geological agent the sea acts in three ways: it erodes rocks, and it transports and accumulates sediment. We shall consider, first, its work of erosion, and the various forms assumed by rock-masses which are subjected to its action.

1. **Erosion.**—Although there can be no doubt that the sea acts chemically upon rocks, yet that action is neither so conspicuous nor important as the mechanical action of waves and currents. Submerged reefs of limestone, however, often show a highly honey-combed and irregular surface as if they had been attacked by acidulated water, and it is probable therefore that some portion of the calcium carbonate held in solution by sea-water may have been obtained directly from submerged limestone-rocks. Again, certain igneous rocks, which are rich in basic silicates, are often altered by the chemical action of the sea—some silicates being converted into carbonates.[1] But it is the erosion produced by mechanical action which chiefly claims our attention. This action is confined for the most part to that marginal belt within which waves and breakers work. We have seen that the erosive power of a river increases with the volume and velocity of its current. It is the same with waves and breakers—the higher these are and the greater the force with which they break upon a coast, the more effectively do they accomplish their work of destruction. During storms blocks are hurled forward which at ordinary times no wave could move. It is on record that masses of rock weighing more than 200 tons have been turned over and broken; and Stevenson

[1] For some account of the chemical action of sea-water on deep-sea accumulations, see p. 90.

mentions the case of a block of gneiss, some 50 tons in weight, which was moved by the waves at Barrahead in the Hebrides.

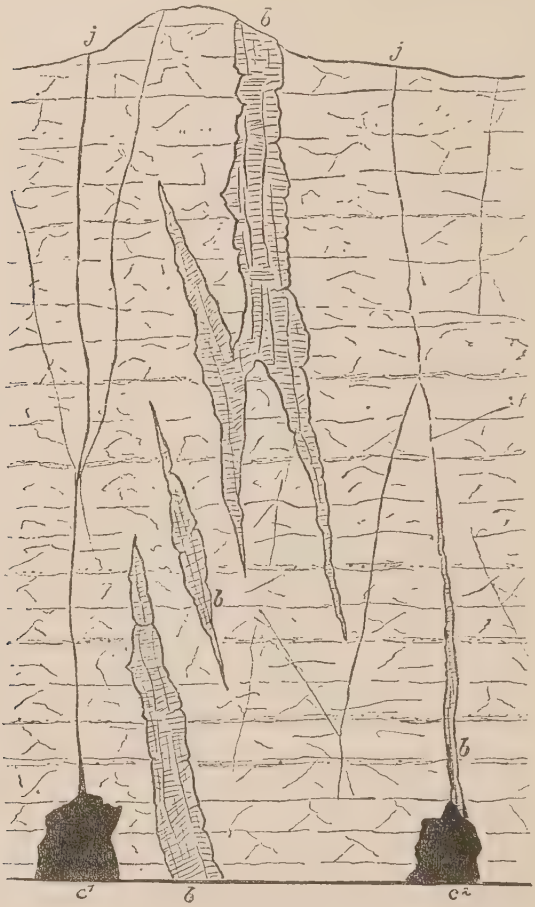


Fig. 37.—EROSION OF SEA-CAVES IN BASALT-DYKES AND ALONG LINES OF JOINTING (FAERÖE ISLANDS).

b b, Basalt dykes ; *j j*, joints ; c^1 c^2, caves.

Under the impact of such waves rocks which are much jointed readily give way—mere hydraulic pressure exerted upon the water in their fissures and crevices tends to loosen and disrupt the rocks;

and a like effect is produced by the sudden compression and expansion of the air in similar crevices during the advance and retreat of great waves. Hence it is the more highly-jointed and fissured rocks which as a rule yield most rapidly to the action of the waves upon an exposed line of cliff. This is well seen in the formation of sea-caves in the Faeröe Islands. The horizontally-bedded basalts of those islands are traversed by veins and dykes of a very hard and compact basalt—much harder and more compact indeed than the beds which it cuts across. Yet notwithstanding its apparent superior durability, the basalt of the dykes is frequently hollowed out into caves which often penetrate the cliffs for many yards—sometimes indeed when two adjacent dykes cross each other these caves have a double entrance. The ease with which the hard basalt of the caves is eroded arises from the fact that it is always most abundantly cross-jointed. One may even watch the process of cave-erosion in quiet summer weather along the wild west coast of Stromöe. When the long swell sweeps against the cliffs the caves become for the moment obliterated. No sooner does the wave drop than the air, which had been compressed in the numerous clefts and cracks of the basalt, rushes out, and one can see numerous fragments dislodged from roof and wall dropping upon the surface of the water. Now and again this process has been carried so far that the roof is drilled through and a communication ("blow-hole") is formed with the surface, through which, during storms, water rushes out, scattering stones and boulders high in the air, like a kind of aqueous volcano.

Formation of Cliffs, Rock-terraces, and Beaches.—But

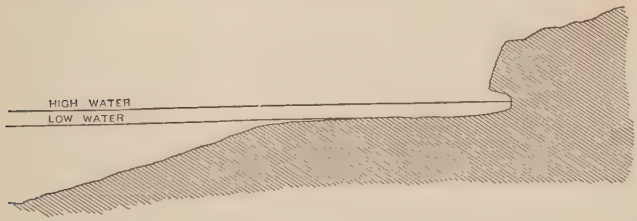


Fig. 38.—formation of sea-beach.

just as rivers with little or no sediment would have inconsiderable eroding power, so the sea, without the aid of its detritus, would be much less destructive in its action upon a shore-line. It is this detritus set in motion by waves and breakers which enables these to accomplish most of their work. The general action of the waves upon a coast is illustrated in the annexed diagram (fig. 38). The

rocks attacked by the breakers are gradually undermined, and from time to time larger and smaller masses give way and fall to the base, where they serve to protect the cliff until they themselves are broken up and converted into shingle, gravel, and sand. By the constant advance and retreat of the waves rock-fragments are ground, and rubbed, and rounded, and gradually reduced in size, while the platform of rock over which they are swept to and fro is continually undergoing abrasion, and constantly increases in width as the cliffs are eaten back by the battering of the detritus which the waves and breakers hurl against them.

(*a*) *Form of Cliff and Beach in Comparatively Homogeneous Rock-masses.*—Rocks of somewhat homogeneous composition, which yield more or less equally to the action of the sea, tend to form regular lines of cliff, while the beach in front shows an even surface. In such lines of cliff there is a general absence of caves. Some massive sandstones, chalk occasionally, and clay frequently, afford examples of this kind of cliff and foreshore.

(*b*) *Form of Cliff and Beach in Rock-masses of Variable Composi-*

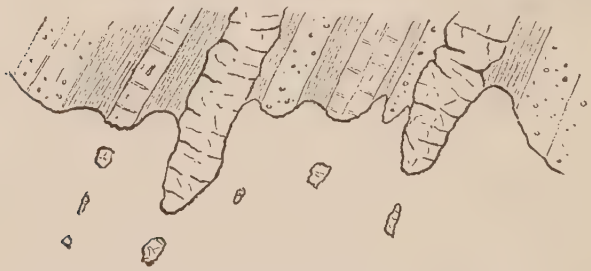


Fig. 39.—GROUND-PLAN OF SEA-COAST.
Irregular outline due to alternation of durable and less durable rocks.

tion.—Where rocks of variable composition form the sea-coast the cliffs and foreshore show a corresponding variety of configuration. The cliffs are generally very irregular in form and outline—the less coherent or more readily eroded rocks being worn out into caves and gullies, while the more durable rocks form headlands and buttresses. The foreshore, instead of showing an equal surface, is usually diversified with gullies and trenches, and projecting knobs and masses—some of which may rise far above the surface of the highest tides. Isolated stacks, islets, reefs, and skerries are generally common upon such a coast. All these islets and reefs of course mark former positions of the coast-line, and owe their existence simply to the fact that they are composed of less readily

eroded material than the more yielding rock-masses by which they were formerly encompassed (fig. 39).

(*c*) *Influence of Rock-structure upon the Form of Cliffs.*—The forms assumed by sea-cliffs not only vary according to the composition and texture of the rocks, but they are also greatly influenced by the structural peculiarities displayed by rock-masses. Many rocks, for example, are arranged in regular beds, horizontally disposed, like a pile of books placed one on top of the other; others

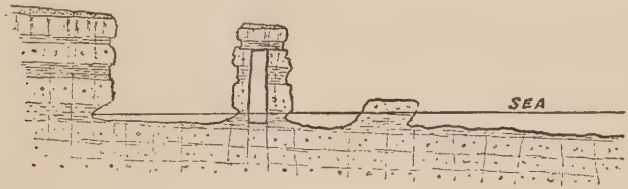


Fig. 40.—SECTION OF SEA-COAST ERODED IN APPROXIMATELY HORIZONTAL STRATA.

again show inclined bedding, the inclination being sometimes gentle and sometimes steep; while yet other bedded rocks are vertical, like rows of books in a library. Again, there are certain kinds of rock which have no bedded arrangement whatsoever. Now all rocks, as we have already learned, are traversed to a smaller or greater extent by division-planes. Sometimes such division-planes are most regular; at other times, however, they are very irregular, and this is frequently the case with massive rocks

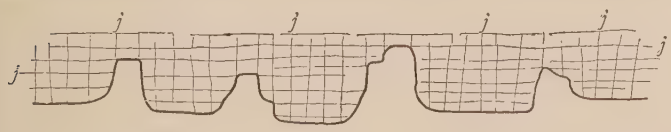


Fig. 41.— GROUND-PLAN OF SEA-CLIFFS CUT IN HORIZONTAL STRATA. *j j*, Lines of jointing.

which show no trace of a bedded arrangement. Cliffs built up of *horizontal strata* or *beds* are generally vertical or approximately so. This is owing largely to the presence of division-planes, of which there are two sets, both vertical and intersecting each other at right angles or nearly so. Waves and breakers, which tend to excavate hollows at the base of all cliffs, gradually undermine the horizontal strata until at last the overlying masses, losing their support, give way along a division-plane, and thus a fresh vertical face of rock is exposed (fig. 40). But as the beds are fissured by two sets of joints it often happens that they break up irregularly, and the line of cliffs becomes indented, as it were, by larger and smaller rectangular recesses—the wall-like faces of which are defined by natural

division-planes (fig. 41). *Strata* that are *inclined seaward* often display overhanging cliffs. This is due in like manner to the presence of division-planes, which are perpendicular to the planes of bedding. A glance at the section (fig. 42) will show that while the beds incline seaward the division-planes incline inland. Here

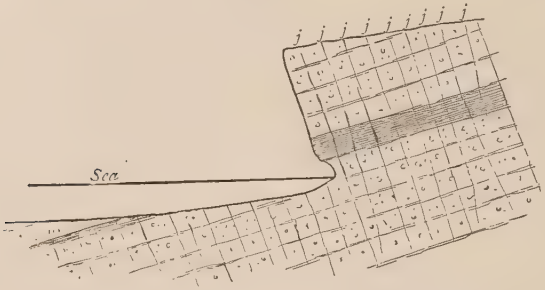


Fig. 42.—SECTION OF SEA-CLIFFS: STRATA DIPPING SEAWARD.
j j, Joints.

again the cliff-faces are defined by the division-planes *j j*, which are lines of weakness along which the undermined strata give way. Owing to the presence of the double set of division-planes such overhanging cliffs are apt to exhibit the same kind of rectangular arrangement as is shown in ground-plan in fig. 41. Now and again strata that are inclined seaward show no well-marked cliffs,

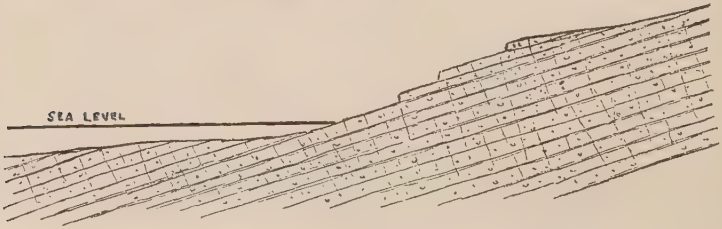


Fig. 43.—SECTION OF SEA-COAST: STRATA DIPPING SEAWARD.

but rather form sloping banks (fig. 43), which act as natural breakwaters. In cases of this kind erosion is at a minimum. *Strata inclined towards the land* generally give rise to cliffs that slope seawards. In such cases the cliff-faces are defined by joint-planes, as a reference to fig. 44 will show. Thus it may be said that the form assumed by sea-cliffs cut out of bedded rocks is largely determined by division-planes. The cliffs may consist of very variable

kinds of rock and thus become highly diversified in detail, but when they are viewed broadly it will be found that they owe their dominant features to structural peculiarities, amongst which the most important are joints. It must not be supposed, however, that all strata are jointed as regularly and conspicuously as is shown in the preceding diagrams. Sometimes the division-planes are very poorly developed, and they are often enough irregular and inconstant in their trend. When such is the case we may expect to find similar irregularities in the contour of sea-cliffs. Thus, many massive crystalline rocks may give rise to cliffs of almost any form. These may slope away from the sea, or they may overhang it,

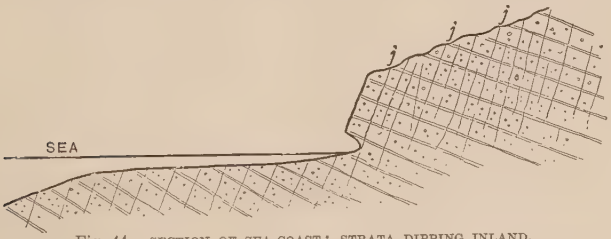


Fig. 44.—SECTION OF SEA-COAST: STRATA DIPPING INLAND.
j j, Joints.

while their general trend will be apt to be very irregular—now advancing in bold precipitous headlands, now retreating and again running out into rugged points, and showing at intervals more or less frequent caves, gullies, inlets, and bays. Such irregularities are due very often to the irregular character of the fissures that divide the rocks. But in all cases the composition and texture of the rocks, whether these are bedded or not, necessarily influence the configuration assumed by rock-masses under the action of the sea. Hence, although the dominant features presented by a line of cliffs are frequently determined by rock-structure, yet often enough the influence of this last is obscured by the mode in which the rocks break up and crumble down under the action of rain, frost, and springs. These agents, indeed, attack and modify the rocks of a sea-coast cliff in precisely the same manner as they effect the destruction of river-cliffs and escarpments. It is chiefly for this reason that the cliffs of a coast-line generally slope to the sea. In many cases the havoc produced by springs and frosts in such cliffs really exceeds the work done by waves and breakers.

Under certain conditions marine erosion upon a coast-line is retarded by the accumulation of débris at the base of cliffs. Thus in the case of chalk-cliffs, while the chalk is readily pounded down

to a fine sediment and removed, the hard flints derived from it tend to accumulate and form banks of shingle which act as natural breakwaters, and so to some extent safe-guard the cliffs from the ruder assaults of breakers.

2. Transport and Accumulation of Sediment.—Detritus carried down to the sea by rivers or derived from a coast-line by the action of waves and breakers is distributed by tidal currents over the sea-floor—the coarser material gathering along the shore in shallow water, while the finer sediment is swept out to deeper water and spread over wider areas. At very considerable depths no coarse detritus is accumulated. But to this there are some exceptions. Stones of various sizes, for example, may now and again be dropped into deep water from melting ice-rafts. Sometimes also stones and débris entangled in the roots of drifted trees, or attached to sea-weeds, may be carried far out to sea. Again, enormous quantities of certain spongiform volcanic rocks (pumice) are often floated seawards; and a large proportion of this material must eventually fall to the bottom. Finally, submarine volcanic eruptions must frequently cumber the bed of the ocean with fragmentary material of various kinds. Notwithstanding these exceptions the general rule holds good—namely, that coarse terrigenous (land-derived) débris is distributed over a somewhat narrow belt, and that as the sea-bed deepens land-derived sediment becomes finer and finer.

Littoral or Shore-Accumulations.—These accumulations extend from high tide-mark down to some distance below low water. It is, of course, upon the belt lying between tide-marks that wave-action is most continuous and the production of detritus most apparent. By this action of the waves gravel and shingle are eventually heaped up in certain places and arranged in banks which extend along the shore; while the finer-grained material is swept outwards by tidal currents to deeper water. The gravel-banks are somewhat lenticular in form, but are usually thickest on the shoreward side, while they thin off seaward more gradually, and often pass horizontally into grit and sand. Littoral deposits, as we should expect, are generally very irregularly bedded. Some of the coarser shingle-banks, indeed, show no trace of any bedding, but are mere piles of rounded stones and boulders. Where grit and sand, however, are commingled with gravel the bedding-lines are more or less distinct. Such deposits are made up of rapidly-alternating lenticular and wedge-shaped layers and beds, the arrangements of the materials pointing to confused current-action. Now and again nests and lenticular patches and thicker layers of fine-grained sediment may occur among coarser littoral deposits, in

nooks and hollows which are more or less sheltered from breaker-action. *Ripple-marks* or *current-marks* are common in all the finer-grained sediments that form within the littoral zone. They are due to the action of gentle currents, and are quite analogous in origin to the ripple-marks seen in blown sand-dunes. The soft sand or mud is washed up into ridgelets by an advancing tide,—the ridgelets being arranged at right angles to the path of the current, with their shorter and steeper slope facing the direction in which the water moves. When a tide is going back the crests of the ridgelets are generally smoothed off, and not infrequently a new set of ripple-marks is produced, the steeper slopes of which look seawards. Walking along a sea-shore we are struck with the constantly changing character of the beach-deposits. In some places these may be composed of shingle and gravel alone, in other places sand prevails, and in yet other places, especially upon the coasts of estuaries and in some quiet bays, mud and silt are apt to predominate. In the coarser-grained detritus organic remains seldom abound, and they are generally represented by water-worn fragments of littoral forms. But in quiet bays the shore-deposits, consisting usually of sand and very fine gravel, are often abundantly charged with shell-débris. Summing up the general characters of littoral accumulations, we should say that these are liable to more or less rapid change, not only vertically, but also horizontally, in the direction of the coast-line; that the coarser deposits which occur close in-shore graduate into finer-grained accumulations as they pass out to sea; that diagonal or current-bedding is common; that ripple-marks are of frequent occurrence in the finer sediments; that

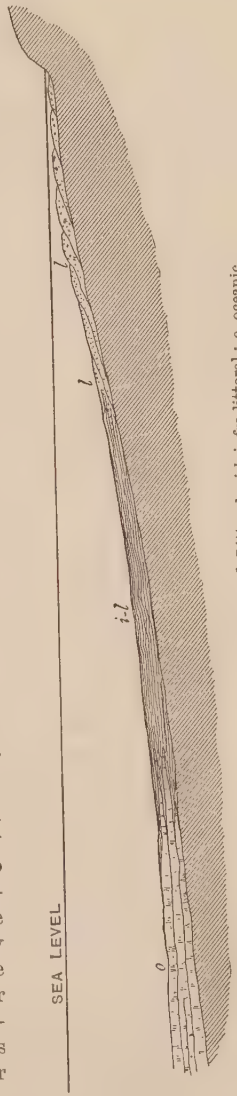


Fig. 45.—MARINE FORMATIONS. *l*, Littoral; *i-l*, infra-littoral; *o*, oceanic.

organic remains often abound in these latter while they are not so plentiful in the coarser gravels and shingles.

Infra-littoral and Oceanic Accumulations.—These accumulations extend from the littoral zone down to a depth of 2000 feet or more, and to a distance of sixty to three hundred miles from shore. No hard and fast line, as may well be supposed, separates littoral from infra-littoral and oceanic deposits; the former pass into the latter. This passage is marked by the gradual and successive disappearance of fine gravel, grit, and sand, and the increase of mud, silt, and clay. Could we trace approximately a line which should mark the boundary between littoral and infra-littoral and oceanic deposits we should find that this boundary is very irregular. Where the sea suddenly deepens the infra-littoral beds would commence at no great distance from the shore, while the littoral deposits would advance far out to sea in places where the water deepens more gradually. Now and again, owing to the action of particular currents, sandy sediment is swept well out to sea beyond the littoral and even the infra-littoral zone, so that locally the oceanic region may become the receptacle of more or less pure arenaceous deposits. But as the influence of currents upon the transport of such comparatively coarse sediment soon ceases in deep water, sandy deposits seldom extend for any distance into the true oceanic area. This area, therefore, receives chiefly the finer-grained material derived from the waste of the land—namely, clay, silt, and mud. Such deposits will be characterised not only by their finer-grained character but also by their wider distribution: they will be spread over vastly greater areas than the infra-littoral and littoral accumulations. As a rule they will show little trace of diagonal or confused bedding, since the currents to which such an arrangement is due act very feebly in deep water. Their bedding will be therefore more or less regular. Over the bed of the oceanic region marine organisms often abound, and these will become embedded in the accumulating sediment, and will therefore escape the rolling and trituration which so generally characterise the organic remains of littoral deposits. Here and there marine organisms may be so abundant that the slowly-growing sediments may be very largely composed of shells and other hard parts. Occasionally waifs from the land—plants or animals—may be drifted out to sea, and sinking to the bottom their remains will become embedded along with those of marine organisms. Around volcanic islands and coral islands which rise abruptly from great depths the oceanic deposits will often be highly charged with loose volcanic ejectamenta, or with decomposed volcanic materials and calcareous mud. MM. Murray and Renard, in describing the fine-

grained terrigenous sediments that gather in the deeper water around continents and islands which are neither of volcanic nor coral origin, distinguish three kinds of mud—blue, red, and green. The blue muds are found extending around the great continents and larger islands, and they occur in all enclosed or partially enclosed seas. The blue colour is due to the presence of decomposed organic matter. Among their ingredients particles of quartz, often rounded, are most abundant; and these are associated with particles of many other minerals, all of them derived from the rocks that form the nearest lands. Those mineral ingredients have a diameter of 0·5 mm. and less; but now and then fragments of rocks 2 centimetres in diameter occur. Calcareous organisms are sometimes plentiful in the clay and sometimes absent, while the remains of diatoms and radiolarians are usually present. The green muds differ from the blue muds chiefly in colour, and in the presence of a considerable quantity of granular glauconite,[1] which is often found filling the shells of foraminifera and other organisms. Occasionally they are associated with green sands which differ from the muds only in the comparative absence of argillaceous matter and the greater abundance of grains of glauconite. The colour of these green deposits appears to be due chiefly to this mineral, but sometimes to protoxide of iron. Red muds owe their colour to the quantity of ochreous matter which is carried down by some rivers to the sea.

Abysmal or Pelagic Accumulations.—The fine muds of the deeper portions of the oceanic area, all of which are terrigenous, gradually pass into sediments that contain no land-derived materials. The tidal currents, as we have seen, succeed in sweeping sand out from the littoral and infra-littoral zones to the borders of the oceanic area, but their transporting power lessens as the water deepens, so that only the very finest sediment ever reaches the deeper parts of the area in question. As the sea-bottom shelves down to greater depths the terrigenous sediments are succeeded by a *red clay* and various kinds of *ooze*, made up largely of the dead shells of foraminifera, pteropods, heteropods, and radiolarians, and the frustules of diatoms. These organic accumulations will be described on a succeeding page. The red clay, according to Murray and Renard, is the most widely distributed of all the pelagic or abysmal deposits. Indeed, it seems to form a certain proportion of all the deep-sea organic oozes, and may be said therefore to exist everywhere in the abysmal regions of the oceanic basins. Its deep brown or red colour is due to the presence of the

[1] A dirty greenish mineral composed of silicate of iron, potash, and alumina.

oxides of iron and manganese. The grains are extremely fine, rarely exceeding 0·05 mm. in diameter. Scattered through the deposit occur grains of various minerals of volcanic origin, together with fragments of lapilli and pumice more or less altered or decomposed. Such materials may have been ejected from terrestrial volcanoes and carried by the winds or floated by currents to great distances; or they may to some extent be the relics of submarine eruptions. Such is the general character of the ingredients in the red clay wherever that deposit has been met with in deep-sea soundings. It is evidently the result of the chemical action of sea-water on products of volcanic origin; the volcanic débris has been gradually decomposed and transformed into argillaceous matter. Many facts conspire to show that its formation is an extremely slow process. Thus remains of vertebrates, consisting of the ear-bones of whales, beaks of ziphius, and teeth of sharks, are often plentifully present: the less resistant portions of the skeletons of those animals being absent; and there is no reason to suppose, as MM. Murray and Renard point out, that the parts of the ocean where these remains occur are more frequented by sharks and whales than other regions where they are rarely or never dredged up. Of these remains, some have every appearance of having lain upon the sea-bottom for a very long time; others belong to extinct species, and many are either partially coated or surrounded with thick layers of manganese-iron. In the same red clays occur metallic spherules which are of cosmic origin, in other words, meteoric dust. The accumulation of all these substances in such relatively great abundance shows us that the oceanic basins have remained unchanged for a vast period of time, and assures us that the formation of the abysmal red clay is extremely slow.

CHAPTER IX.

GEOLOGICAL ACTION OF PLANTS AND ANIMALS.

Destructive action—Protective or conservative action—Reproductive action—Vegetable soils and peat—Mangrove-swamps—Nullipores—Organic oozes—Coral formations; theories of their origin—Shell-marl—Shell-sand—Shell-breccia—Bone-breccia—Guano.

The action of plants and animals in modifying the surface of the earth is obvious in our own day, and the records of geology abundantly testify to the importance of this action in past ages. In some cases plants and animals aid in the destruction of rocks; at other times they rather protect than destroy; while frequently by their growth and decay they give rise to new accumulations.

1. Destructive Action.—The destructive action of plants is well seen in the penetration of rock-crevices by roots, which as they grow wedge the masses asunder. When this takes place on steep slopes and cliffs it often leads to the fall of much débris. Moreover, the opening of such crevices, by allowing freer percolation of water, prepares the way for the action of frost and thus accelerates disintegration and disruption. Again, vegetation (forests and bogs) attracts rain and so tends to increase the flow and erosive action of streams and rivers. Above all the chemical action of rain is much intensified by the acids (carbonic acid, humus acids) which it obtains from decaying organic matter. The destructive action of animals is illustrated by the boring of rocks by *Saxicava*, *Pholas*, and other molluscs, and sometimes by annelids, echini, and sponges. Rocks so drilled are weakened and fall more readily before the battering of the breakers. Corals and molluscs are likewise attacked and killed by boring species, and in this way the crumbling of their hard parts is accelerated. Fishes, preying upon molluscs and echinoderms, often give rise to great heaps and banks of broken shells, as off the coast of Maine in North America. The drainage of a district is sometimes modified by the dam-building operations of the beaver. The tunnelling of the ground by burrowing

animals, such as mole and rabbit, occasionally results in the draining of lakelets and ponds ; and the similar operations of the cray-fish (crustacean) upon the embankments of the Mississippi, has so weakened these in places that they not infrequently give way, and the water rushing through floods the low grounds. The action of worms in the formation of soil has been studied in detail by Darwin. He shows that their burrows penetrate five or six feet or even more, and that the worms are continually bringing up finely-levigated soil to the surface which is removed to lower levels by rain, so that a kind of constant circulation of soil is going on—the loss at the surface being made good by material brought up from below. Humus acid is generated in the bodies of the worms and thus is enabled to act upon rocks and rock-fragments at some distance from the surface, while the small particles of stones are triturated in the gizzards of the worms. "In many parts of England," according to Darwin, "a weight of more than ten tons of dry earth passes through their bodies, and is brought to the surface on each acre of land ; so that the whole superficial bed of vegetable mould passes through their bodies in the course of every few years." According to Professor Henry Drummond the white ants in Central Africa are equally important geological agents. The ground is tunnelled by them in all directions and immense quantities of material brought up to the surface to form their earthworks and "hills," all of which are washed down and carried away in the rainy season to fertilise remoter valleys or to be swept onward in the rivers to the ocean.

2. Protective or Conservative Action.—It is chiefly plants that are conservative. This action is exemplified in the fixing of blowing sand-dunes by the growth of tufts of grass and other plants. Earthy slopes are likewise protected by turf from erosion by rain, while vegetation on the banks of lakes and streams prevents these being so readily undermined by the water during storms, freshets, and floods. Not infrequently shrubs and trees serve to increase the height of river-banks by arresting detritus and sticks and rafts of driftwood. In hilly districts woods and forests, by equalising and regulating the flow of the water of precipitation, prevent the wholesale destruction of soils and subsoils by torrent-action. This is well illustrated by what has taken place in various countries where the forests have been improvidently destroyed. Thus it has been calculated that since the felling of the woods in the Ligurian Provinces of Italy four-tenths of the area have been divested of soil by rains and floods. In Southern France similar destruction has followed the clearing of the great forests. In 1842 the Department of the Lower Alps possessed some 245,000

acres of cultivated soil; in 1852 only 184,000 acres remained, so that 61,000 acres had been swept bare by torrents and floods in ten years. The later census returns show a progressive diminution in the population of all the provinces which were formerly remarkable for their forests. In high mountain-lands, such as Switzerland, forests often protect the valleys from the assaults of destructive avalanches, and are now planted and carefully preserved for that purpose. In some regions the rocks along a shore-line are protected in some measure from breaker-action by calcareous algæ and ordinary sea-weeds. Similar protection, as Professor Herdman has pointed out, is occasionally afforded by sponges, hydroid zoophytes, tube-forming worms (*Serpula*, *Spirorbis*), the common acorn-shell (*Balanus*), certain polyzoa (as *Lepralia*, *Membranipora*), gregarious molluscs (oysters, mussels), and some species of simple and compound ascidians. Coral-reefs, also, act as breakwaters upon certain coasts, and minimise the destructive influence of the sea.

3. Reproductive Action—Vegetable Soils and Peat.—The action of plants and animals often results in the formation of new deposits. Soil, as we have seen, is to a considerable extent composed of inorganic materials which have been modified by the action of worms. All soils contain a certain percentage of organic matter, while some are largely composed of decayed vegetable remains. Such, for example, is the rich black cotton soil of India. In temperate and cold-temperate regions the continuous growth and decay of certain plants, such as *Sphagnum*, result in the formation of *peat-mosses* or *bogs*, and *morasses*, which often attain a depth or thickness of many feet. The most extensive areas of peat-moss or bog occur upon flat-lying ground, where the layer of vegetable matter varies in thickness from a foot or so up to ten or fifteen yards. Sometimes it clothes considerable slopes and covers the tops of broad mountains, but in such positions it rarely exceeds a few feet in thickness. The upper few feet of a bed of peat are usually somewhat loose and spongy in texture, but the texture gradually becomes closer lower down, until at the bottom the substance may appear as close and compact as some kinds of lignite. Peat is distributed over considerable areas in the north of Europe, where it may occur from the highest to the lowest levels of the land, as in our own islands, Scandinavia, North Germany, and Holland. In the south of Europe it occurs chiefly amongst the mountains. In like manner large bogs abound in North America, especially in Canada and the northern states of the Union, and they are met with also in Fuegia, South America. Under some peat-bogs lacustrine deposits make their appearance. These are often characterised by the presence of shell-marl, and now and

again they have yielded remains of such animals as Irish deer, stag, oxen, etc., and relics of man belonging to the Neolithic and later archæological ages. Another characteristic of many peat-bogs is the occurrence in them of trees. Sometimes these are rooted in the soils underlying the peat, or they may occur at one or more successive levels in the peat itself. The occurrence of these successive layers of trees in the bogs points to changing physical and climatic conditions, as will be shown later on.[1] A temperate or cold-temperate and humid climate seems to favour most the growth of peat-bogs, as may be inferred from the fact that they flourish vigorously where such conditions prevail. In many places where peat formerly grew and spread, its increase seems now to be arrested, the rate of decay exceeding that of growth, from which we may suppose that the conditions in such places have become less favourable. Many attempts have been made to estimate the rate at which peat grows, but nothing can be more misleading than to take the known rate of growth in some particular place as a standard of measurement by which to judge of the antiquity of all other bogs. The fact is that growth is regulated by the supply of moisture and physical conditions. Not only does peat form at different rates in different regions, but the same is often the case in one and the same bog—the bog being dry in some places and actually wasting and crumbling away, while in other portions the mosses may be flourishing more or less luxuriantly.

Mangrove Swamps.—Mention has already been made of the protection afforded to the banks of streams and lakes by vegetation. The sea-coast in some tropical countries is similarly protected by the mangrove and other plants. Such trees, dropping new roots from their branches into the water, entangle and retain detritus and floating vegetable matter, and, continually advancing into the shallow sea, eventually succeed in fringing the land with belts of dense jungle and swamp.

Nullipores, etc.—These calcareous algæ and ordinary seaweeds, as already remarked, have a protective influence upon seacoasts, by sheltering the rocks from breaker-action, but the former are most noteworthy from the fact that they abstract carbonate of lime from the sea-water, and by their growth form occasionally large beds, as among the reefs of the Florida Seas. Some moisture-loving plants (*Hypnum*) have the same power of taking up carbonate of lime and encrusting themselves with it, and in this way considerable accumulations of calc-sinter are sometimes formed. Bog-iron ore owes its origin also to the presence in marshes and stagnant water of the humus acids (derived from decomposing vegetable matter), which

[1] See chapter xxv.

abstract iron-salts from the rocks and soils. These, under the influence of the atmosphere, are subsequently precipitated as hydrated ferric oxide. According to Herdman, the tube-forming annelid, *Sabellaria alveolata*, gives rise to reefs of a coarsely-porous rock, consisting of innumerable closely-placed tubes, which are formed of agglutinated grains of sand.

Organic Oozes.—Deep-sea researches have shown that the abysmal portions of the sea-bottom are in many places covered with various kinds of ooze—largely composed of the shells and skeletons of minute pelagic organisms which have fallen to the bottom from the surface. MM. Murray and Renard distinguish four kinds of organic ooze, each characterised by the relative predominance of certain forms, or by the presence of characteristic species. *Globigerina ooze* contains over 40 per cent of carbonate of lime, and consists principally of the dead shells of pelagic foraminifera (*Globigerina*, *Orbulina*, *Pulvinulina*, etc.) Sometimes the percentage of lime is as much as 95—that is, the ooze consists almost entirely of organic débris. The colour of the deposit depends chiefly upon the relative abundance of the oxides of iron and manganese, and may be white, yellow, brown, or rose. It is a fine-grained deposit—its non-organic constituents consisting of the same substances as compose the *red clay* described in a preceding paragraph. Besides shells of foraminifera, frustules of diatoms and skeletons of radiolarians occur in variable quantities—sometimes forming 20 per cent of the deposit, and at other times being comparatively rare. *Pteropod ooze* is of the same general character as globigerina ooze, but differs from it in the greater number and variety of pelagic organisms, and especially in the presence of pteropod and heteropod shells. *Diatom ooze* is of a pale straw colour, and consists principally of the frustules of diatoms. When dry it is a dirty white siliceous flour. It contains about 25 per cent of carbonate of lime, which exists in the form of small globigerina shells and other organisms. Some 50 per cent of the whole deposit consists of frustules of diatoms and skeletons of siliceous organisms. *Radiolarian ooze* is composed chiefly of the skeletons of radiolarians, and is reddish or dark brown in colour owing to the presence of oxides of iron and manganese. In all the oozes now mentioned there is always a larger or smaller percentage of argillaceous and other inorganic matter, which has been recognised as forming the abysmal red clay. So that this red clay may be said to exist everywhere throughout the deepest portions of the oceanic basin. Diatoms also occur in fresh water and form considerable accumulations, 20 to 35 feet thick, in some lakes. The so-called *infusorial earth* or *Tripoli powder* is of this origin. The finer varieties contain over 90 per cent of silica.

Coral Formations.—In the warmer regions of the ocean many islands and reefs appear to be composed almost entirely of the calcareous skeletons of Actinozoa. Such reef-builders do not flourish in water of a lower temperature than 68° F., and consequently they are not met with in temperate latitudes. There are many coasts also within tropical regions where they do not occur, owing sometimes to the presence of cold extra-tropical currents, sometimes to the muddy character of the water where large rivers enter the sea, and now and then to the great depth of the sea off precipitous coasts, for reef-builders do not flourish at greater depths than 100 feet. An *atoll* or coral island commonly consists of a narrow, more or less oval or irregular, reef surrounding a lagoon. Such reefs vary from two or three up to fifty miles in length, but the dry land is not necessarily continuous with them. In many cases this only appears in little patches at irregular intervals—or the windward side of an atoll may form an island, while the leeward side is swept by the waves. *Barrier reefs* are those which encircle or rise in front of steep land, from which they are separated by a navigable channel. *Fringing reefs*, again, are those that extend outwards from the shore until the increasing depth stops their farther advance. The rock of a coral reef is a white limestone composed chiefly of coral, but containing often shells and other organic remains. Owing to the percolation of acidulated water through the rock it frequently loses all trace of organic structure, and assumes a compact or finely crystalline texture. Occasionally it shows a concretionary or oolitic appearance, looking as if made up of rounded grains and pellets. In other places the organic structure is not effaced, and corals and shells can be clearly distinguished—the rock sometimes forming a kind of breccia or conglomeration of broken shells and coral-débris—while sometimes the corals stand as they grew, the spaces between them being filled in with coral-sand and triturated fragments and grit of coral and shell. Coral-sand is formed by the waves and breakers on the beach, and being driven upwards by the wind becomes eventually cemented by percolating water into a calcareous sandstone. It is the action of the breakers and the wind, indeed, which forms the islets upon a reef—the waves tearing off large masses of coral and coral-rock from the outer edge, and hurling these to the top of the reef, where they serve to arrest the sands and grits carried forward by the winds. The actual thickness attained by reefs is not known. They appear to rise frequently from depths of one or two thousand feet and more, and these depths were, until recently, supposed to indicate the actual thickness of the coral-rock. But the observations of Mr. Murray and others make this conclusion somewhat doubtful. One

of the most important reefs is the great barrier reef of North East Australia, which, with a variable breadth of 10 to 90 miles, extends along the Australian coast for a distance of 1250 miles. In some places the depth immediately outside of this reef exceeds 1800 feet.

A beautiful theory was advanced by Mr. Darwin to account for the existence of such reefs. According to him each atoll has passed through the successive stages of fringing reef and barrier reef. As reef-building corals do not flourish at greater depths than 100[1] feet it is evident that the foundation of a coral reef could not have been laid in deeper water. Now, as such moderate depths occur only round islands and off the shores of continents the reef-builders would begin their work by forming at first a fringing reef. Slow subsidence of the sea-bottom is supposed to have supervened, but while the foundations were being carried down the corals continued

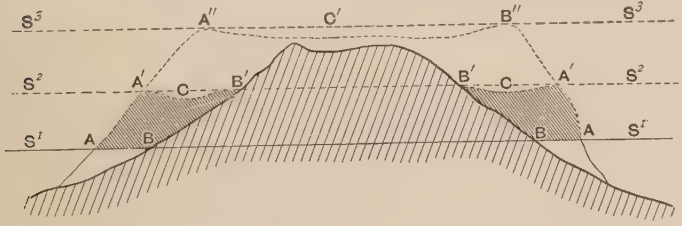


Fig. 46.—DARWIN'S THEORY OF CORAL ISLANDS.

A B, A B, Fringing-reef encircling an island, while the sea-level is at S^1 S^1; A′ B′, A′ B′, barrier-reef, with lagoon C, with the sea-level at S^2 S^2; A″ B″, atoll with central lagoon C′ over site of drowned island, the sea-level being at S^3 S^3.

to grow upwards, the building of the reef keeping pace with the sinking of the sea-bottom. Thus by and by the fringing reef is converted into a barrier reef. We have now only to suppose that the movement of subsidence and the labours of the corals continue until the reef-encircled island disappears below the waves, and a complete atoll will be the final result. The accompanying diagram-section across an atoll brings into view the general features of Mr. Darwin's theory.

The line S^1 represents the relative level of land and sea during the initial stage—a central island, encircled by a fringing reef B. By continuous subsidence of the sea-bottom and corresponding upward growth of coral the fringing reef is converted into a barrier reef A′ B′, with a lagoon C C. By and by the central island disappears below the level of the sea S^3, its site being occupied by a lagoon C′, and the barrier reef becomes an atoll.

Up to within a few years ago Mr. Darwin's theory was very

[1] Some observers give the limiting range at 50 or 60 fathoms.

generally accepted by geologists, but the recent researches of Mr. Murray during the celebrated voyage of the *Challenger* suggested to this naturalist another explanation of the phenomena of coral reefs. He points out that all the islets surrounded by coral reefs are of volcanic origin, and that no trace of any general subsidence, such as Darwin's theory requires, can be detected. If it were true that coral reefs are monuments marking the site of continental islands or masses of land, surely the islets that still remain unsubmerged, fringed and ringed with reefs, might be expected to contain other kinds of rock than volcanic lavas and tuffs. He thinks it most probable therefore, that the reefs have simply been built up from the tops and slopes of submerged and partially submerged volcanic banks and mountains. To the objection that it is difficult to believe that so many volcanic banks and cones should occur just at the proper depth from the surface, Mr. Murray replies that it is not necessary to suppose that all the submarine eminences were of equal or nearly equal height. Some may have risen at first above the level of the sea and subsequently have been reduced by the action of waves and breakers to the condition of shoals: while others that did not reach to the limits within which reef-builders live may have been brought up to that zone by the gradual accumulation upon them of organic débris. Pelagic forms of life flourish in extraordinary numbers in the surface-waters of the tropics where reefs abound, and their shells and skeletons are constantly falling to the bottom, where, along with the exuviæ of creatures living at the bottom, they must in time form very considerable deposits. In this manner submarine volcanic banks and cones will gradually be heightened until they are brought up to the zone in which a varied and abundant fauna can flourish. The exuviæ of this profuse life will now accelerate the growth of the calcareous accumulation, and so by and by the depths at which corals can live will be reached, and a reef will begin to grow upwards to the surface. A little consideration will show that reefs growing upwards from a submarine bank would necessarily assume the form of atolls. It is on the outskirts of reefs exposed to the free dash of the waves that the corals flourish best—inside the lagoons their growth is less rapid—they are stunted and often dead. Consequently we may infer that during the upward growth of a reef from the bottom the outer or peripheral portions of a colony, being better placed as regards food supply, will have the advantage of those corals that are growing in the centre of the mass; and this difference must increase as the reef approaches nearer to the surface. Atolls, then, according to Mr. Murray, have grown upwards from the tops of submarine banks—the lagoons being deepened by the

removal of dead coral-rock, which is dissolved by the carbonic acid of the sea-water. Fringing reefs, he believes, are converted into barrier reefs by the simple growth of the coral, and do not require any process of subsidence to explain them. They simply grow outwards upon a talus of their own débris, which is forced off from the edge of the reef by the breakers. Large blocks, sometimes 20 or 30 feet long, torn from the reef, tumble down the steep seaward face of the reef, where they form a steep talus, on the summit of which the coral-builders extend their reef. Mr. Murray's views receive some support from the observations of Professor A. Agassiz on the coral reefs of the Florida Seas and the West India Islands. Recent researches among the Solomon Islands also render it certain that some coral reefs have really had the origin ascribed to them by Mr. Murray and Professor Agassiz. For in those islands Dr. Guppy found calcareous deposits at heights of 100 to 1100 or 1200 feet, which were composed of a mass of impure, partially consolidated, limestone (charged abundantly with foraminifera and other pelagic forms), covered with a comparatively thin crust of coral-rock. This structure is exactly what Mr. Murray's theory would lead us to expect.

But although this theory does away with the necessity of any such widespread subsidence as Mr. Darwin desiderated, it does not forbid the probability that some coral reefs may have originated in the manner supposed by the latter.

Shell-marl, Shell-sand, Shell-breccia, etc.—Reference has been made to the fact that the exuviæ of molluscs and other testaceæ accumulate here and there in sufficient quantities to form considerable beds. Such is the *shell-marl* so often found in the beds of lakes; the *shell-sand* composed of the triturated remains of shells, etc., so common upon the shores of quiet bays of the sea; and the heaps of shells and shell-débris with remains of other organisms which gather now and again along some shores, and are occasionally consolidated into rock by the percolation of acidulated water, forming *shell-breccia.*

Bone-breccias.—Accumulations of bones are formed in caves and other retreats by predaceous animals, and such accumulations in limestone-caves may become agglutinated together by the drip of water from the roof, and so form *bone-breccias.*

Guano, composed of the droppings of sea-birds, occurs in the comparatively rainless islands lying off the west coasts of South America and Southern Africa. It forms beds which may reach a thickness of 30 to 90 feet. It contains about 20 per cent of phosphate of lime.

CHAPTER X.

CLASSIFICATION OF THE PRODUCTS OF EPIGENE OR SURFACE-ACTION.

Mechanically-formed, chemically-formed, and organically-derived products—Comparison of certain rocks with products of recent superficial or epigene action—Petrology of bedded or stratified rocks—Systems of classification—Geological classification of rocks produced by epigene action.

Before proceeding to consider the action of the hypogene forces it will be well to bring into view some of the general results we have now obtained from a study of the work done by the superficial agents. Our object at present is to glance at a few of the distinguishing features presented by the products of epigene action and to compare these with the leading characters of some of the more common rocks which enter into the composition of the earth's crust. It is maintained by geologists that these rocks have been produced by actions the same in kind as those that are now modifying the surface of the earth. If this be true, then there should be a close general resemblance between such rocks and modern accumulations. For each kind of rock we ought to find some corresponding formation being built up under the influence of causes now in action. To facilitate comparison we may attempt some convenient classification of the products of epigene action—such as will bring prominently into view leading characters and distinguishing features. We have seen, then, that the products of surface-action have resulted partly from the mechanical and chemical agency of the atmosphere, of water, and of ice, and partly from the operation of plants and animals. In many cases these actions are so involved that it is hard or even impossible to separate the one from the other, and therefore any classification we adopt must be more or less artificial and unsatisfactory. Nevertheless it will serve to facilitate progress if we provisionally arrange the materials we have been studying under these three heads :—

1. Mechanically-formed products.
2. Chemically-formed products.

3. Organically-derived products.

Mechanically-formed Products are by far the most numerous and abundant. Under this head come all the products of the action of wind and "weathering" (dunes and disintegrated materials) as well as all those aqueous deposits which are the result of the mechanical action of water and of frost and ice—namely, gravel, sand, and mud, moraines, etc. The products of wind-action and of "weathering" we term (1) *Eolian* or *Aërial;* the materials brought together by the mechanical action of water are (2) *Sedimentary;* and those which owe their origin to frost and ice are called (3) *Glacial* products.

Chemically-formed Products, are typically represented by rock-salt, gypsum, stalactites and stalagmites, etc. They have been precipitated from water in which they were previously held in solution, and very often show a crystalline structure.

Organically-derived Products.—These are composed in large measure of the remains of organic structures, such as peat, coral-rock, organic oozes, etc.

Now a little consideration will show that no hard and fast line can be drawn between those three groups. Some accumulations, as we have seen, are very composite in their character, being made up partly of sedimentary and party of chemically-formed materials. Others again consist of a mixture of mechanical, chemical, and organic accumulations—so that our provisional arrangement is very artificial. It will, however, pave the way to a more natural classification which we shall presently attempt. Meanwhile, we must consider the character of a number of rocks and compare these with our mechanically, chemically, and organically-formed products.

COMPARISON OF CERTAIN ROCKS WITH PRODUCTS OF RECENT EPIGENE ACTION.[1]

1. **Mechanically-formed Products** consist of fragmental materials; they are granular, non-crystalline aggregates, the constituent ingredients of which may be angular or rounded in form, and may or may not be arranged in layers. This definition includes all the Aërial or Eolian, the Sedimentary, and the Glacial

[1] In the following rock-descriptions reference is unavoidably made to various minerals, rocks, and geological formations of which some account will be given in later pages. The student cannot therefore be expected to follow at first all that is mentioned in the present chapter. He should read it carefully now, and return to its perusal after he has made some acquaintance with the rock-forming minerals and rocks described in chaps. xii. and xviii.

accumulations. Now there are a number of rocks which answer generally to the same description, and with these we must make some acquaintance.

(1) Aërial or Eolian Rocks.—*Blown sand* is the most typical form of Eolian accumulation. In some regions where it is composed of calcareous ingredients it has been converted into hard rock by the percolation of rain-water containing carbonic acid in solution. The acidulated water dissolves some of the calcareous matter and redeposits it in the manner already explained, and in this way what was formerly a loose incoherent sand becomes compacted into a solid calcareous rock. Some very thick and widely distributed sandstones in South Australia are believed by some observers to have had an Eolian origin. They show many of the characteristics of wind-blown deposits, but the evidence is not conclusive. Very few sandstones of such an origin have yet been certainly recognised, and these are chiefly of recent geological age —such as the calcareous sandstones or limestones of the Bahamas and Bermudas. The *dust-deposits* now forming in various parts of the world appear likewise to be without corresponding accumulations among formations of any antiquity. Indeed, as will be afterwards pointed out, terrestrial deposits are of rather exceptional occurrence in these strata—the larger proportion of which are fresh-water and marine accumulations.

Under the head of Aërial products come all those accumulations which owe their origin more or less directly to the action known as "weathering." Amongst these are included the following :—

Rock-débris, forming taluses and banks or "screes," on slopes and at the foot of cliffs ; much of this material is no doubt produced by the action of frost. When such rock-débris is compacted into a solid rock it is known as *Breccia* (see *postea*) ; *Kaolin* or *China-clay*, the result of the decomposition of highly felspathic rocks, such as granite ; it generally contains granules of quartz and plates of mica—the less readily decomposed portions of the original rock. *Pipe-clay* (see p. 106) is probably in many cases, like kaolin, merely a product of the decomposition of highly felspathic rocks. *Fuller's-earth*, a hydrous aluminous silicate, not unlike clay in appearance, but not at all plastic ; yellowish green or brown in colour, greasy or unctuous, falling to pieces in water ; in some cases seems to be the result of the decomposition of basic igneous rocks, as of gabbro, in Saxony, occurs in beds in the Jurassic and Cretaceous formations of England.

(2) Sedimentary Rocks.—The rocks which are believed to be due to the mechanical action of water form various terms of a series represented by *Conglomerate* (puddingstone), *Sandstone*, and *Shale*.

(*a*) *Conglomerate* consists of a mass of various-sized rounded stones, cemented together. It is obviously gravel compacted into a solid mass. The included stones exactly resemble those which we see rolled about by the action of water—the sole difference between it and loose gravel and shingle being its consolidation. The stones may consist of any kind of rock or mineral, but the harder kinds—those which can best resist disintegration are apt to preponderate. Consequently quartz and quartz-rock are very common ingredients in many conglomerates. As the materials of a conglomerate have rarely travelled very far, they will generally be made up of the débris of other rocks in the neighbourhood. Thus in the Old-Red-Sandstone conglomerates that flank the Highlands of Scotland, many of the stones consist of quartz, quartz-rock, schists, slates, granite, and various igneous rocks, most of which have been brought down from the adjacent heights. *Limestone-conglomerate*, *quartz-conglomerate*, etc., are names given to rocks in which limestone, quartz, etc., predominate. At other times it is not so much the character of the stones as the nature of the cementing material which may constitute the distinguishing feature of a conglomerate. Hence we have such names as *siliceous*, *calcareous*, and *ferruginous* conglomerates, according as the material by which the stones are bound together consists of silica, carbonate of lime, or iron oxides. Now and again the stones and their matrix of grit and sand or clay are held together without any cementing material. The mass has become indurated simply through its own weight or the pressure of superincumbent masses of rock, and the squeezing and compression which, as we shall afterwards learn, are the result of earth-movements. Like coarse gravel and shingle, some conglomerates are very tumultuous in appearance—having no lines or planes of deposition. Very frequently, however, they show rudely alternating layers of finer and coarser materials, and now and again the arrangement of the stones themselves—overlapping the one upon the other—betrays distinctly the aqueous origin of the deposit and the direction in which the water flowed. *Pebbly-conglomerate* is composed of small well water-worn stones ; *boulder-conglomerate* is made up of large stones and boulders.

(*b*) *Breccia.*—An aggregate of angular and sub-angular fragments of minerals, rocks, or organic remains compacted into a solid mass by some cementing matter. Some conglomerates (*brecciated conglomerates*), pass into such a rock by the presence of an increasing proportion of angular stones. But a true breccia consisting of angular stones exclusively can hardly be included among aqueous sedimentary rocks. Breccias have originated in many different ways. Sometimes they are of the nature of those "screes" or

taluses of rock-débris which are due to the action of frost and other agents ; others, again, have been formed by hypogene action, as will afterwards be pointed out. True breccias, however, now and again occur interstratified with ordinary sedimentary rocks. At the present day similar angular débris falls from cliffs into lakes and into the sea, in places where little wave- or current-action goes on, as, for example, along the coasts of many fiords. In such places the angular stones will eventually become embedded in sand and clay, which will pass out seawards into deposits containing no angular débris. The word breccia should never be used as a rock-name without some descriptive or qualifying adjective or noun, such as limestone-breccia, quartz-breccia, bone-breccia, volcanic-breccia, friction-breccia.

(*c*) *Sandstone.*—The aqueous origin of this rock is hardly less conspicuous than that of conglomerate, for it is evidently only consolidated sand. It is made up of grains of quartz or other mineral and rock-matter, compacted into a solid mass, either by mere pressure, or by the partial solution or fusion of its own substance, or by the infiltration of some cementing material, such as silica, carbonate of lime, or oxides of iron. Moreover, it is usually arranged in layers or beds of variable thickness. Some sandstones are so fine in the grain that their granular character can hardly be seen without the aid of a lens ; others again are very coarse—the granules being as large as small peas, and between the finest and coarsest varieties there is every gradation. Most sandstones are composed of the least destructible mineral, quartz—sometimes to the exclusion of all other mineral matter. But very often flakes of mica are present, and sometimes so numerous are these that the sandstone is rendered more or less fissile. Occasionally sandstones consist chiefly of felspathic matter—grains of felspar, which are usually somewhat decomposed and earthy like. Now and again they contain a large admixture of argillaceous matter or clay. And not infrequently they may be made up to some extent of calcareous matter, such as the comminuted débris of shells and corals, mixed with grit of quartz and other minerals ; or the calcareous matter may be of chemical origin, having been originally diffused through the bed, and subsequently become irregularly aggregated, so as to impart to the rock a somewhat concretionary structure. Rock of this kind is called *cornstone.* The grains in a sandstone are generally more or less rounded, as if by water-action ; sometimes, however, they are angular, or there may be a mixture of rounded and angular grains. They are seldom so well rounded as the grains of sand-dunes which occur at a distance from the sea. Occasionally, rolled grit and water-worn stones occur scattered at

intervals through a sandstone ; and not infrequently little patches and rounded pieces of clay occur in the same way. These last are called *clay galls.* Sandstones show many varieties of colour, but grey, yellow, and red predominate. Pure white sandstones usually contain no iron—and are generally composed of granules of milky quartz, or of a mixture of milk-white and clear quartz. The red colours of many sandstones are due to the presence of peroxide of iron, which envelops each grain. Brown and yellow colours are due in like manner to coatings of the hydrous peroxide of iron, while green may arise from the presence of the same substance or of a silicate of iron. Many sandstones which when freshly opened up are grey or blue in colour become brown or yellow by exposure. This is due to the oxidation of the iron which they contain. Black sandstones owe their hue to the presence of carbonaceous matter.

The following are varieties of sandstone :—*Freestone* or *liver-rock,* a rock of homogeneous composition which may be worked *freely* in any direction ; occurs usually in thick massive beds. *Flagstone,* generally a more or less argillaceous sandstone, occurring in thin beds, or in beds which divide easily along the planes of deposition into flags of more or less equable thickness. *Micaceous sandstone,* in which mica is plentifully present ; generally a soft, fissile rock. *Greensand* or *glauconitic sandstone,* a sandstone containing diffused through it grains and spherules of the dirty greenish mineral called glauconite. Many crystalline rocks, to be afterwards described, weather readily into a gritty sand, and thus give rise to sandstones of peculiar character. Such is *arkose,* or granitic sandstone, formed of disintegrated granite ; *volcanic sandstone, trappean sandstone,* etc., composed of disintegrated igneous rocks. The nature of the cementing or binding material when that is conspicuous, also gives rise to such terms as *siliceous, calcareous,* and *ferruginous* sandstones. Clay and carbonaceous matter, when plentifully present, produce *argillaceous, carbonaceous,* and *bituminous* sandstones. When the rock is more or less exclusively composed of quartz or of felspathic matter, we have *quartzose* and *felspathic* sandstones. The coarser varieties of sandstone, which are usually quartzose, are often called *grits.* These pass into fine pebbly conglomerates. There is, in fact, a gradual passage from the very finest grained sandstone into grits, and from these into coarse boulder-conglomerates. Conglomerate and sandstone are merely terms of a natural series.

(*d*) *Greywacké.*—This is an aggregate of rounded sub-angular and angular grains and splinters of quartz, felspar, and slate, sometimes with mica and grains of other minerals and rocks, embedded in a hard paste or matrix, which may consist of siliceous, calcareous,

argillaceous, or felspathic matter. The rock is generally harder than most sandstones. Grey and pale blue are the most common colours, but green, brown, yellow, red, and purple greywackés are not uncommon, and black (anthracitic) varieties are known. All textures are met with from close-grained compact rocks to coarse-grained varieties made up of small angular fragments like a breccia. The finer-grained rocks frequently contain fragments of hard shale and clay, like the corresponding clay-galls in sandstone. It is often impossible to distinguish the granular texture of the finer-grained varieties without the aid of a strong lens. Occasionally the rock takes on an incipient crystalline texture. This is especially the case with felspathic varieties, which are sometimes mistaken for igneous rocks. Frequently solution or fusion of the grains and minute angular fragments seems to have taken place, rendering the rock extremely hard and compact. At other times such peculiarly compact varieties probably owe their hardness to the infiltration of siliceous cement. The rock occurs in thick massive strata like liver-rock, and in thinner beds and layers like ordinary sandstone and flagstone.

(*e*) *Clays.*—These are argillaceous or earthy deposits, consisting chiefly of the silicate and hydrous silicate of alumina, but usually containing a larger or smaller proportion of other ingredients. When moist they are more or less plastic, soft, and sectile, and when breathed upon emit a peculiar earthy smell. They show all shades of red, blue, yellow, green, brown, grey, and white. Amongst varieties are the following: *China-clay* or *Kaolin* (already described, see p. 102); *Pipe-clay*, a fine white plastic clay, very like China-clay, but containing a larger percentage of silica; *Potter's-clay* contains more impurities than pipe-clay; *Brick-clay*, an intimate admixture of finely-divided clay and sand, with a larger or smaller percentage of iron; used for making bricks; *Fire-clay*, a clay containing little or no lime, alkaline earths, or iron (which act as fluxes), and hence infusible or highly refractory, rendering it suitable for the manufacture of bricks and pottery which are required to stand intense heat: of common occurrence in Carboniferous strata.

(*f*) *Mudstone.*—A non-fissile earthy argillaceous rock, containing a variable quantity of sand. It has generally a very irregular fracture. When pounded down and mixed with water it is only very slightly plastic. *Clay-rock*, closely resembles mudstone, but is plastic when ground down and mixed with water.

The clays and mudstones of sedimentary character are without doubt similar in their origin to the finer deposits which are accumulating in lakes and seas at the present day. Some of the

clays when dried split up into thin laminæ, showing that they have been gradually deposited. Occasionally the individual laminæ have their surfaces dusted over, as it were, with extremely fine-grained sand ; and frequently clays pass into argillaceous sandstones. There is thus every gradation from fine plastic clay to sandstone in which no argillaceous matter appears, and from sandstone into conglomerate.

(*g*) *Shale.*—A laminated clay-rock—the individual laminæ marking lines or planes of deposition.[1] It is evidently only a very finely bedded or fissile clay or mud, which has been subsequently somewhat hardened. Such shales show many varieties of colour and texture ; and must be considered as characteristic sedimentary deposits.

(3) Glacial Rocks.—Under this head are included all rocks which are due to the action of frost and ice.

(*a*) *Screes, Rock-rubbish, Breccia*, etc.—The rock-débris formed on slopes and at the foot of cliffs by the action of the atmosphere has already been mentioned under Aërial accumulations. Much of this material doubtless results from the action of frost. Many ancient breccias occurring in some of the older geological formations have probably originated in that way.

(*b*) *Erratic Blocks, Perched Blocks*, etc.—Erratic blocks may occur in strata of marine or fresh-water origin, as in Miocene strata (Hill of the Superga, Turin), in the Chalk at Croydon, in Carboniferous strata (Ohio) ; in Silurian (Ayrshire), etc. In such cases they have been transported by floating-ice. They have also been scattered loosely over the surface of many countries, or embedded in glacial accumulations by the action of land-ice. *Perched blocks* have likewise been transported and left in their present prominent position by land-ice.

(*c*) *Moraines, Morainic débris, Till or Boulder-clay.*—The nature and origin of these have already been fully described (see pp. 55, 68). Certain of the breccias and coarse conglomerates which occur at many different horizons in the sedimentary formations of the earth's crust are believed by some geologists to be of the nature of morainic accumulations, in some cases modified by the mechanical action of water. Such are the great boulder-masses, conglomerates, and breccias of the Cambrian, Silurian, and Old Red Sandstone, Lower Carboniferous, Permian, and some more recent formations.

2. Chemically-formed Rocks.—This subdivision might include a number of rocks which have already been described under the head of Aërial rocks, such as *kaolin* and *fuller's-earth*, which

[1] The lamination of some shales, however, may possibly be a superinduced structure, see *postea* under *Cleavage*.

are due to the chemical action of rain, etc. Among the more typical chemically-formed rocks are the following :—

(1) Stalactites and Stalagmites.—These as already explained (p. 21) are composed of carbonate of lime. They are usually creamy white or yellow in colour, but often show darker shades of brown and red. Internally they commonly show a concentric structure—the laminæ consisting of the thin coats successively formed during the evaporation of the water in which the calcareous matter was dissolved. Frequently this concentric structure is more or less obscured and even entirely obliterated by a superinduced radiating crystalline structure.

(2) Travertine, Tufa, or Calc-sinter, is likewise formed during the evaporation of water containing calcium carbonate. It may be porous and friable or hard and compact. The massive varieties are often distinctly crystalline. White and creamy white or pale yellow are the common colours, but other hues occur, and frequently the rock is variegated and mottled with concentric bands and lines of colour. Some modern accumulations formed by calcareous springs are made up of spherical granules of calcic carbonate, which have a concentric and often a fibrous radiating structure. In many cases these granules contain a nucleus or kernel of some foreign substance, such as a grain of sand, round which the successive layers or coatings of calc-sinter have formed. Such limestones are called *Oolite*, from their resemblance to fish-roe. The coarser varieties are known as *Pea*stone or *Pisolite*. A similar oolitic structure has been observed occasionally in the coral-rock forming the surface of modern reefs—which appears to owe its origin to the movement to and fro of grains of coral-sand in pools or sheltered hollows in which the water is highly saturated with carbonate of lime, derived from the decomposition of dead coral.

(3) Rock-Salt.—A crystalline, granular or rudely crystalline white, translucent, or transparent mass of chloride of sodium or common salt, often stained red by ferruginous clay and other impurities. It occurs in beds of variable thickness, and is often associated with green, red, and variegated clays, with gypsum and with dolomite. The thicker beds of rock-salt (50 to 100 feet) appear to be of lenticular form. It has been precipitated by the evaporation of saturated solutions, either in lakes and seas which had no outlet, or in isolated portions of the sea separated by sand-banks or other barriers from the influence of the open ocean.

(4) Dolomite (Magnesian Limestone).—A crystalline, granular, or sometimes earthy aggregate of the mineral dolomite (double calcium and magnesium carbonate), usually combined with a larger or smaller proportion of calcium carbonate, and often containing small

quantities of other substances, such as quartz, clay, oxides of iron, etc. It is usually grey or yellowish in colour. The rock is often full of irregular fissures and angular cavities, lined with crystals of dolomite. Very frequently it assumes a concretionary structure, the concretions often looking like bunches of grapes, or an aggregated mass of musket-balls or cannon-shot. The concretions have a radiated crystalline structure. Typical dolomite differs from pure limestone in its somewhat greater hardness and higher specific gravity, and in the relative difficulty with which it effervesces with cold hydrochloric acid. It is also more frequently crystalline than limestone, sometimes being made up entirely of small rhombohedral crystals. Some magnesian limestones are more or less plentifully charged with organic remains and have probably had the same origin as limestone (see p. 111), but other varieties are either destitute of organic remains or very poorly stocked with them, and when shells, etc., are present, these are generally dwarfed or stunted forms. Such unfossiliferous dolomites, being frequently associated with rock-salt and gypsum, are believed to have been precipitated chemically upon the bottom of closed lakes and seas.

(5) Gypsum, or hydrous sulphate of lime, sometimes occurs as a rock. It is usually white, soft, and crystalline, but compact, fibrous, and sparry varieties are also not uncommon. Not infrequently it has all the appearance of a white granular limestone, but it is readily distinguished from limestone by its softness (for it may be scratched with the nail), and by its non-effervescence with acids. It is occasionally discoloured by impurities, such as clay, bitumen, and oxides of iron. From the fact of its occurrence in beds in close association with rock-salt and unfossiliferous dolomite we may infer its chemical origin. Like these deposits it appears to have been precipitated from saturated solutions in closed lakes and seas. *Anhydrite*, or anhydrous sulphate of lime, often occurs in beds under similar circumstances. It is harder than gypsum.

(6) Flint.—Greyish-blue, grey, or black, compact, as hard as quartz, with well-marked conchoidal fracture; a mixture of amorphous and crypto-crystalline silica; occurs in nodules and occasional tabular sheets in the Upper Cretaceous strata. The silica of those nodules has probably been largely derived from the hard parts of siliceous organisms, sponges, etc., dissolved by percolating water and again precipitated—so that flint in many cases might just as well be included under the head of organically-derived rocks. *Chert* and *Hornstone* are somewhat impure and splintery varieties of flint. *Lydian-stone* or *Lydite*, is a dark grey or black, very hard, smoothly compact, argillaceous variety, the colour of which is due to the presence of carbonaceous matter. It

generally occurs in thin bands or layers, and is often much rent by fissures which are filled with white quartz. Probably those siliceous rocks may sometimes be products of thermal springs (see *postea*); on the other hand, they can often be well enough accounted for by the chemical action of percolating waters. But the origin of others is still obscure.

(7) Ironstone.—Several varieties of ironstone occur as chemical precipitates, either in beds, or within cavities and fissures of rocks. *Limonite* or *brown hæmatite* (hydrous ferric oxide) is a compact earthy or fibrous rock, pale, yellowish brown to black, with a yellow or light brown streak; occurring in regular beds and irregular fissures in rocks. It is often formed on the bottoms of lakes and under bogs or marshy soil (*bog-iron ore*). Reniform, oolitic, and stalactitic varieties are known. *Hæmatite*, or red iron ore (anhydrous ferric oxide), is a compact, earthy, fibrous, or sometimes crystalline rock; red to black in colour, with a red streak; usually contains some impurities, such as oxide of manganese, silica, or clay; frequently occurs in concretionary masses, filling up subterranean cavities in limestone, and irregular fissures in various other rocks; also met with in regular beds interstratified with crystalline schists, etc. *Magnetite* (magnetic oxide of iron), a granular or compact rock; black, with a black streak and metallic lustre; shows strong magnetism; usually contains admixtures of various minerals, such as specular iron, chlorite, pyrite, quartz, chromic iron, hornblende, felspar, etc. Occurs like hæmatite in association with crystalline schists, forming enormous masses and sheets, as in the Thuringian Forest, at Dannemora in Sweden, at Gellivara in Luleo, Norway, and elsewhere. *Spathic iron ore*, a granular or compact aggregate of siderite (ferrous carbonate), greyish yellow or yellowish brown, with a white or grey streak; occurs in beds or veins. *Clay-ironstone* (sphærosiderite), a granular to compact admixture of siderite and clay with, frequently, organic matter. Occurs as nodules and in beds interstratified with shales and coals in the Carboniferous and other formations. *Pyrite* and *marcasite* (sulphides of iron) occasionally form subordinate layers and beds interstratified with other rocks.

Many other minerals besides the ores of iron occur in large masses in veins and irregular cavities, such as quartz, calcite, fluor-spar, barytes, malachite, the ores of various metals, etc. (see *postea*, under "Ore Deposits").

3. Organically-derived Rocks.—These rocks have sometimes been termed *zoogenic* and *phytogenic*, according as they consist of the relics of animal- or of plant-life. They form a somewhat numerous class, the more commonly occurring kinds being these:—

(1) Limestone.—Under this head come a great series of rocks, ranging in character from soft calcareous earth or shell-marl up to dense compact and crystalline rocks, containing no apparent trace of organic structure. Amongst the organically-derived calcareous accumulations now forming in fresh water and the sea are *shell-marl*, various *organic oozes*, *shell-sand* and *shell-grit* and *breccia*, *coral-rock* and its varieties. All these have their counterparts in older geological formations. Many of these older limestone-rocks are composed entirely and others partially of the calcareous shells and hard parts of molluscs, echinoderms, corals, and other organisms. Such limestones, however, sometimes have undergone in places considerable change, and have locally lost all trace of organic structure, while assuming a superinduced crystalline texture. Occasionally we meet with limestones which are more or less crystalline throughout and contain no recognisable trace of any organic remains, nevertheless it can hardly be doubted that these rocks have often had an organic origin. Those varieties in which an organic structure is most apparent are *chalk*, *crinoidal limestone*, *nummulitic limestone*, etc. *Chalk* is a white, fine-grained, earthy limestone, largely composed of the remains of shells of foraminifera, together with the débris of various other calcareous organic remains, more or less disintegrated and reduced to a fine flour. *Oolite* is often in like manner made up of the remains of calcareous skeletons and exuviæ. *Lacustrine limestone* is generally a thin-bedded, fine-grained, compact, dull white or grey, and often earthy and soft rock—the earthier forms known as *shell-marl* being composed of an aggregate of shells with some admixture of clay. Many varieties of limestone are characterised by the abundance of certain organic remains, and are called *crinoidal* or *encrinite limestone*, *nummulitic* and *orbitoidal limestone*, *shell-limestone* or *muschelkalk*, *hippurite limestone*, *spatangus limestone*, etc., according to the nature of the prevalent or most peculiar fossils. The presence of certain impurities or admixtures of other mineral matter also gives rise to varieties of limestone. Thus we have *argillaceous limestones*, containing a notable proportion of clay ; *ferruginous limestones*, with much ferric oxide ; *siliceous limestone*, with much diffused silica ; *hydraulic limestone*, containing a certain proportion of silica and alumina which forms a mortar that sets in water ; *carbonaceous* or *bituminous limestone*, dark grey or black from the presence of carbonaceous matter. Some carbonaceous limestones emit a fetid odour when struck by a hammer (*fetid limestone*). *Rottenstone* is the name given to the skeleton of a siliceous limestone from which the calcareous part has been removed in solution. *Magnesian limestone* or *dolomite:* limestones containing a very large proportion of the mineral dolomite, have already been

described as probably chemical precipitates. Many magnesian limestones, however, which are poorer in the double calcium and magnesium carbonate, are evidently mainly composed of organic débris. No hard and fast line can be drawn between limestone and dolomite (magnesian limestone). Most limestones contain some percentage of magnesia, and it is only when this is high (say twenty per cent and more) that the rock is entitled to be called a dolomite.

(2) Diatom-Earth (Infusorial earth).—*Tripoli* is composed of the siliceous frustules of diatoms. It occurs as a soft friable earth, but is sometimes a little firmer and more solid, probably from impregnation with opal substance. The more dustlike varieties are called *kieselguhr*. Diatom-earth may be of marine or fresh-water origin, since the minute siliceous plants of whose remains it is chiefly formed occur both in fresh and salt water. It is quite possible that some of the lydian-stones may be old diatom-earths, which through subsequent chemical action have lost all trace of organic structure.

(3) Flint and Chert, as already described, have frequently had an organic origin—either direct or indirect. Some organisms secrete silica from sea-water and build it up in their skeletons ; this is the case with siliceous sponges and diatoms. Sponges abound in the Chalk formation which is characterised by its numerous nodules and irregular layers of flint. Those sponges have often had their silica replaced by carbonate of lime, and the silica so removed has been redeposited in the surrounding chalk, or has in its turn replaced the substance of shells. It is highly probable, indeed, as Professor Sollas believes, that much of the silica appearing as nodules, etc., in the Chalk, has been derived from the siliceous spiculæ of sponges.

(4) Phosphatic Deposits.—Mr. George Hughes has recently described the alteration (in *Araba Island*) of coral-rock into phosphate of lime by the action of water containing soluble phosphates derived from the excrements of sea-birds. Of the guano no trace remains ; but the fragments of coral in the underlying rock have been altered into a substance containing from 78 to 80 per cent of phosphate of lime. Mr. Hughes thinks that this replacement of carbonic acid by phosphoric acid may help to explain the occurrence of phosphatic layers in the Cretaceous formation. Another source of phosphate of lime are *phosphatic nodules* and *coprolites*. The former are concretions formed round bones, etc. ; the latter are the fossil excrements of reptilian fish, reptiles, and mammals. Occasionally these coprolites occur in sufficient quantities to form beds from a few inches to several feet in thickness. Many of the nodules are apparently mere earthy concretions, but they are probably all organically derived. They occur in strata of vastly different ages—

Cambrian, Silurian, Cretaceous, and Pliocene. *Bone-breccia*, a confused mass of mammalian bones and teeth, commingled with angular or sometimes water-worn stones, sand, or red earth, and cemented into a rock by calcareous matter, occurs in fissures and on the floors of caves in limestone. *Bone-beds*, made up chiefly of the remains of reptiles and fishes, are met with in several geological formations.

(5) Peat (Turf, Bog) is an aggregate of vegetable growth—chiefly of marsh-loving plants, such as *Sphagnum*, *Hypnum*, *Polytrichum*, etc. —closely interwoven and more or less compressed and decomposed ; colour varies often in same bed from light brown above to dark brown or black below. The vegetable matter is not much changed. In the upper portions the peat may be growing, and is soft and spongy ; a little farther down it is somewhat firmer, but its vegetable structure is quite apparent ; at the bottom the vegetable substance is more decomposed, and the peat becomes somewhat compact, but is often softer than butter and easily dug. When dried the upper portions of a bed of peat are felt-like, somewhat resembling compressed hay, while the bottom part may be tough, and almost compact, like some kinds of lignite. The amount of ash varies very much—some varieties containing less than 1 per cent, others over 60 per cent.

(6) Brown Coal or Lignite.—An earthy or compact mass of chemically altered vegetable matter, brown or black in colour, and usually more inflammable than common coal. There are many varieties of lignite. Some retain the texture of the vegetable matter, appearing to be made up of fragments of wood irregularly matted together. Others show a laminated structure, this structure being the result of pressure, or, sometimes, it is in consequence of the lignite being largely composed of leaves. Such varieties often contain insect-remains—wing-cases of beetles especially. Yet other kinds are very compact and almost black, with a shining fracture like pitch. Lignite contains 55 to 75 per cent of carbon, and has a specific gravity of 0·5 to 1·5. The ash is very variable in amount, as much so as in the case of peat. The chief repositories of lignite are strata of Tertiary age ; it occurs, however, exceptionally in some of the older formations.

(7) Common Coal.—A black, compact, carbonaceous mass, in which as a rule no vegetable structure can be detected by the unaided eye ; not so inflammable as brown coal. It contains from 75 to 85 per cent of carbon, its specific gravity varying from 1·2 to 1·5. There are many varieties of coal, such as *caking coal*, which has a short uneven fracture, and fuses or runs together on the fire ; *splint* or *hard coal*, with a more distinct cubical cleavage,

not so friable or shattery nor so readily kindled as caking coal, does not cake or run together; *cherry* or *soft coal*, velvet-black, with shining resinous lustre, does not cake or fuse, has a clear shaly fracture, more readily lighted than splint coal; *cannel* or *parrot coal*, so called from its burning with a clear flame like a candle, and from its chattering or crackling; is compact, with a shaly or conchoidal fracture; its lustre may be dull or brilliant and waxy; does not soil the fingers. Now and again one may see upon the bedding-planes of some coals flakes of a dull black, silky, fibrous substance, which has a distinctly vegetable structure; and occasionally portions of what appears to be the bark of trees may be observed. But generally we require the aid of the microscope to detect the vegetable structure of coals. Some coals seem to be largely composed of the spores or spore-cases of lycopodiaceous plants, allied to our present club-moss. Coal occurs in many formations (Palæozoic, Mesozoic, and Cainozoic), and is usually associated with fire-clay, shales, and sandstones. Most of the seams are the result of growth *in situ*—they mark old land-surfaces—but some would appear rather to be made up of drifted vegetation.

(8) Anthracite or Stone Coal is black, with a kind of metallic lustre, is not easily ignited, and burns nearly without smoke or smell, giving out an intense heat. It consists almost entirely of carbon, and contains only a small proportion of the constituents of bitumen. Altogether it has a more mineralised or "stony" look than common coal. Specific gravity 1·5 to 1·7. Occurs usually in beds like common coal, of which it may be considered as only a more mineralised variety.

Thus peat, lignite, coal, and anthracite represent so many different stages in the conversion of vegetable matter into a mineralised substance from which the oxygen, hydrogen, and nitrogen of the original vegetable structures have been almost entirely eliminated. This is shown by comparing the average chemical composition (neglecting the ash) of the four carbonaceous substances in question:—

		Carbon.	Hydrogen, Oxygen, and Nitrogen.
Peat	contains	60·5	39·5.
Lignite	,,	65·5	34·5.
Coal	,,	82·5	17·5.
Anthracite	,,	92·5	7·5.

The oxygen and hydrogen eliminated during the slow chemical alteration of the vegetable substances unites with a portion of the carbon to form carbonic acid and marsh gas—the choke-damp and fire-damp of the miners.

(9) Oil-Shale (Bituminous Shale).—A dark grey, brown, or black highly bituminous shale, from which mineral oil can be extracted by slow distillation ; occurs like any ordinary shale ; is often charged with organic remains, both plants and animals ; abounds in some of the Carboniferous tracts of Scotland, also locally in the Trias, Lias, and Tertiary of Germany.

(10) Graphite (Plumbago) is a greyish-black or black, soft, flaky, or compact rock ; has a greasy feel, and is not inflammable ; soils the fingers ; consists chiefly of carbon with some admixture of silica, clay, oxides of iron, etc. ; [occurs as a mineral in scales and flakes diffused through various schists, slates, and limestones of the older geological formations, also as a rock in lenticular beds amongst such strata, or in nests and pockets in these and certain crystalline rocks such as granite and gneiss]. Locally it is only an extreme form of anthracite, some coals having been converted into graphite by the heat derived from intrusions of igneous rock, as at New Cumnock in Ayrshire, and near Shotts in Lanarkshire.

The destructive distillation of organic remains stored up in the strata of the earth's crust has given rise to various other products, such as the *mineral oils* (petroleum) and *mineral pitch* (asphalt) which occur in various formations. Sometimes these are found diffused through the body of a rock or stored in fissures and cavities, or they may rise to the surface in a fluid or semifluid condition. Some of the best known localities for the abundant occurrence of petroleum are Baku on the Caspian, Northern Pennsylvania, and Canada. Pitch-lakes occur on the borders of the Dead Sea, and in Trinidad, where there is a pitch-lake 1½ mile in circumference.

(11) Iron Ores.—Mention has already been made of various iron ores under the head of chemically-formed rocks. In the formation of some of these plants have had a considerable share, either indirectly through the chemical actions arising from their decay, or directly in the separation of iron from the water by the living organism, as Ehrenberg supposed was the case with diatoms. Clay-ironstone nodules often contain in the centre some organic matter, such as a coprolite, fish, or portion of a plant, at other times no internal nucleus is visible. The shales in which nodules and layers of this ironstone occur are often abundantly charged with plant-remains, and now and again the clay-ironstone is itself so highly impregnated with vegetable débris that it can be calcined without the admixture of coal. Such carbonaceous clay-ironstones are called *blackband ironstone.* They often contain shells, fish-teeth, and other animal-remains.

Having now briefly reviewed some of the more common rocks which are believed to owe their origin to the action of epigene

agents, we see that these rocks are practically identical with products which are being formed by the same agents at present. The only striking difference between the two series is the general solidification of the older products. But such solidification is no more than we should expect. The older products have been long exposed to the action of percolating waters; in many cases they have been subjected to the influence of subterranean heat, and to enormous pressure, and therefore we are not surprised to find that they should exhibit the effects which would be most likely to arise from such conditions. But while solidification is the general character of the older products, this is by no means invariably the case, neither are the modern products always soft and incoherent. Occasionally we meet with hard sandstone and conglomerate of quite recent age, containing relics of civilised man, just as we now and then encounter widespread deposits of unconsolidated sand and clay which belong to vastly older periods. Again, many limestones of modern age are as hard and compact as any that pertain to the old formations. Anthracite and graphite no doubt differ very much in appearance from peat and other recent vegetable accumulations, but all stages of mineralisation can be traced, from vegetable matter in which the organic structure can be plainly seen by the naked eye up to substances in which no such structure can be detected even by the microscope. And we are perfectly justified in concluding that coal and anthracite, and in many cases graphite also, owe their origin in the first place to the action of life. No hard and fast line, in short, can be drawn between the modern and ancient products of epigene action, and such being the case, geologists have termed all these products *rocks*. Thus, any mass of organic or inorganic matter which is due to the action of natural causes, whether it be soft or hard, and whether it consists of one kind or species of mineral, or of many species is called a *rock*.

The preceding classification of epigene rocks is confessedly artificial; and, indeed, no classification can be otherwise. Our classification is based upon the mode in which the various rocks have been formed, and often compels us to arrange under different heads rocks having the same composition. Thus we have chemically-formed and organically-derived limestones. Then, again, some rocks, such as flint, and certain iron ores, owe their origin partly to organic and partly to chemical action, and must therefore appear under both heads. Once more, many rocks consist of nearly equal parts of inorganic and organic débris, and might be arranged with equal justification, either under the head of mechanically-formed or organically-derived rocks. But a purely petrological arrangement of rocks is even more artificial. Classified solely according to their

characters as rocks, the most discordant substances are brought into juxtaposition. Thus under the heading of "Simple rocks," *i.e.* rocks composed of one mineral substance, we find rock-salt, lydian-stone, coal, ironstones, and various crystalline rocks which fall to be described in later pages. Again, under the division of "Fragmental or Clastic Rocks," are included conglomerate, and various rocks of volcanic origin. Or if we adopt the petrological arrangement of other authors, and group our rocks under the heads of "Crystalline" and "Non-crystalline or Fragmental," we shall put some of our limestones into the crystalline group along with granite, lava, and other crystalline rocks, and others we shall range along with coal, conglomerate, clay, etc., in the fragmental class. Perhaps the most satisfactory grouping for our purpose is a geological one, which has reference not merely to the mode or manner in which the rocks have been formed, but also to the physical conditions under which they were amassed.

CLASSIFICATION OF ROCKS DUE TO ACTION OF EPIGENE AGENTS.

I. TERRESTRIAL.

1. MECHANICAL.

a. Formations due to action of atmosphere ("*weathering*" includes action of frost and chemical action of rain) :—Soils and subsoils; dirt-beds; under-clays of coals; rock-débris, screes, some breccias; "earth-glaciers;" rain-wash, some clays and loams; cave-earth.

b. Formations due to action of wind :—Dust accumulations; blown sand; some sandstones.

c. Formations due to action of land-ice :—Superficial moraines, bottom-moraines, till or boulder-clay; perched blocks and erratics; shattered rock-surfaces, striated rock-surfaces, *roches moutonnées*.

d. Formations due to action of sub-glacial waters :—Aqueous deposits enclosed in bottom-moraines and till as part and parcel of these; giants' kettles and their contents.

2. CHEMICAL.

Formations due to chemical action of rain and underground water :—Some products of this action included under "weathering;" stalactites, stalagmites; calc-sinter; siliceous sinter, and other deposits from springs, etc. [Alterations in rocks by chemical action of percolating water not considered here.]

3. ORGANIC.

a. Formations due to action of animals :—Guano, etc.; bone-breccias in caves.

b. Formations due to action of plants :—Peat, mangrove-swamps, jungle-growths, etc.; lignite; coal; anthracite; some graphite.

II. FLUVIATILE.

MECHANICAL.

Shingle, gravel, sand, etc., forming terraces in river-valleys; some conglomerates and conglomeratic sandstones. Fluviatile deposits merge into lacustrine or estuarine as the case may be.

III. LACUSTRINE.

A. *Formations in fresh-water lakes.*

1. MECHANICAL.

Thin-bedded deposits of sandstone (sand), and shale (clay and mud), with occasional conglomerates (gravel and shingle).

2. CHEMICAL.

Limestone; occasionally with chert.

3. ORGANIC.

Shell-marl; limestone; some iron ores; diatom-earth; some beds of drifted vegetable matter.

N.B.—Organic remains are often plentiful in the mechanical, and sometimes in the chemical series.

B. *Formations in salt-water lakes.*

1. MECHANICAL.

Red and variegated sandstones, clays, etc.

2. CHEMICAL.

Lenticular layers and masses of rock-salt, gypsum, anhydrite, and dolomite.

3. ORGANIC.

Organic remains either wanting or rare. When marine forms occur they are generally dwarfed or stunted. No rocks of organic origin.

IV. ESTUARINE.

1. MECHANICAL.

Thin-bedded sandstone (sand), and shale (mud and clay); beds often interosculate; conglomerate (gravel) rare.

2. CHEMICAL.

Chemical precipitates of carbonate of lime very rare and local.

3. ORGANIC.

Calcareous mud; impure limestone. Organic remains often very plentiful in all the deposits; frequently give evidence of alternations of fresh-water, brackish-water, and marine conditions. Traces of terrestrial life not uncommon. Occasional layers and beds of drifted vegetable matter.

V. MARINE.

A. *Littoral Zone.*

1. MECHANICAL.

Conglomerate (gravel and shingle), grit (coarse sand), and sandstone (sand); irregular bedding; strata thicken and thin out rapidly. Organic remains not plentiful in coarser beds of conglomerate; generally broken and rolled.

2. ORGANIC.

Arenaceous shell-limestone and shell-breccia.

B. *Infra-Littoral Zone.*

1. MECHANICAL.
   Widespread and regularly-bedded fine-grained sandstones (sand), and shales (clay and mud)—the latter predominating. Fossils often abundant in all the deposits of the infra-littoral zone.
2. ORGANIC.
   Impure argillaceous limestones.

C. *Oceanic Zone.*

1. MECHANICAL.
   Fine clay (shale) of terrigenous materials.
2. ORGANIC.
   Organic oozes; coral-rock and mud derived therefrom: thick and widespread limestones; chalk. Most of the oceanic accumulations are organic in origin.

D. *Pelagic or Abysmal Zone.*

1. MECHANICAL.
   No terrigenous materials, save occasional stones dropped from floating ice or drifted plants.
2. CHEMICAL.
   Red clay derived from the decomposition of volcanic rocks.
3. ORGANIC.
   Various organic oozes.

[*Note.*—Erratics carried by floating ice or other agency may occur in lacustrine, estuarine, or marine deposits. Accumulations laid down in lakes, estuaries, etc., by water flowing from glaciers usually consist of fine clay. Chemical formations of more or less local occurrence are not included in above table.]

CHAPTER XI.

VOLCANOES AND VOLCANIC PRODUCTS.

Subterranean, plutonic, or hypogene action—Limits of our knowledge—Volcanoes—Phenomena of volcanic action—Volcanic products: lava, fragmentary ejecta, gases and vapours, hot and mineral springs—Geysers—Structure of volcanic cones; cones of non-volcanic materials, tuff-and-cinder cones, lava cones, composite cones—Petrological character of lava.

Of the nature of the changes which are going on at great depths in or underneath the crust of the earth we can of course know nothing by direct observation. We may indeed infer the existence of certain conditions from the phenomena displayed by modern volcanoes; but all that we actually observe are the products of volcanic action, and the effect of that action upon a volcanic mountain itself and the surrounding neighbourhood. Again, with regard to movements of the solid land—whether of subsidence or elevation—and whether catastrophic and sudden or gradual and protracted—we know really nothing more than that such movements do take place. And it is obvious that any explanation of their cause, however probable it may seem, can never amount to a demonstration. Once more, we may speculate upon the effect likely to be produced by subterranean heat upon rocks buried deep below the surface; or we may form certain views as to the nature and structure of the materials now in a state of fusion or which are cooling and consolidating at great depths—but as those operations take place under conditions which cannot be reproduced in our laboratories, it is evident that we cannot attain to certain knowledge of their nature either by direct observation or experiment. In short, while the work of the epigene agents is carried on to a large extent under our eyes, that of the hypogene forces is for the most part concealed. Nevertheless, geologists are not left so much to mere guessing and speculating as to what is going on in the ground beneath our feet as the student might suppose. The examination of the fragmentary relics of ancient volcanoes, in this and other countries where volcanic action

has long been extinct, has enabled us to picture to ourselves many details of the structure of those interior and basal parts of a volcanic mountain which otherwise must ever have remained unknown. The long-continued action of the agents of denudation has often removed those superficial rock-masses which gather around volcanic orifices, so as to lay bare, as in a dissection, the interior and basal portions—showing us the fractured and baked strata through which the heated gases, molten matter, and loose ejectamenta were erupted, and the dykes and veins of crystalline rock which were injected into the cracks and fissures of the shattered strata. Nay, a study of those vast masses and sheets of schistoze rocks of which large portions of the Scottish Highlands, Scandinavia, and other countries are composed, induces the belief that these rocks may in large part have originally existed as ordinary sedimentary strata, and that their present crystalline condition has been assumed at a time when they were deeply buried underneath other and of course younger strata. And thus we have hints given us as to what may be taking place now throughout extensive areas underneath the surface of the earth. If, therefore, it be true that a study of forces now in action enables us to understand what changes have been effected by those forces in past ages, it is not less true that geological investigations frequently increase our acquaintance with forces now in action, and give us some insight into the hidden operations of nature. It is not indeed too much to say that in many cases our knowledge of such operations is derived in large measure from an examination of the effects produced by the natural forces in past ages.

I.—VOLCANOES AND VOLCANIC ERUPTIONS.

A volcano is a more or less conical hill or mountain, usually truncated, and communicating with the interior of the earth by a pipe or funnel, through which issue hot vapours and gases, and frequently loose fragmentary materials and streams of molten rock. The pipe or funnel may be a vertical hole blown out by the subterranean forces through otherwise continuous and undisturbed rock-masses, or it may be an aperture upon a line of fracture or rent in the crust. In the former case the volcano will usually be small ; and should several such volcanoes occur in the same neighbourhood they will generally be irregularly distributed. There is reason to believe that all the larger volcanoes occur upon lines of fracture, and their linear arrangement or grouping along more or less well-defined belts harmonises with this view. All modern volcanic eruptions appear to take place from isolated points or foci,

but in prehistoric times molten matter seems frequently to have welled up and overflowed from long lines of fissure. These last are known as "fissure eruptions."

Confining attention at present to what is known of existing volcanoes we find that some of these are much more active than others. A few may be said to be in a state of permanent eruption, such for example as Stromboli, which has been constantly active since the time of Homer; Izalco (on the west coast of Central America), which had no existence before 1770, has continued in activity ever since, and is now about 2500 feet high. Other examples of constantly active volcanoes are those of Masaya and Amatitlan in Nicaragua, Sangay in the Andes of Quito, Cotopaxi, Sion in the Moluccas, and Tofua in the Friendly Islands. Many volcanoes, again, after continuing in a state of moderate activity for longer or shorter periods become quiescent, and after a repose of months or centuries, wake up to renew their labours. Vesuvius may be cited as an example. For nearly a hundred years this volcano has been intermittent in its action—the intervals between successive eruptive phases having generally lasted only a few months. So long as the eruptions are constant or very frequent they are rarely violent, but after a period of prolonged repose they are apt to be excessive or paroxysmal. Such was the famous eruption of Vesuvius in A.D. 79. Before that date this mountain had exhibited no signs of volcanic activity. It was completely dormant at the time of the colonisation of South Italy by the Greeks, and there was no tradition that it had ever been active within the memory of man. Wild vines covered the rough rocks on the upper part of the cone, while the richest fields and vineyards clothed the lower declivities. The eruption which succeeded this prolonged state of repose was correspondingly violent, and was followed by a period of comparative tranquillity. Not a few of the greatest volcanoes may be said to exhibit the "phase of prolonged intermittences and paroxysmal eruptions." This is the case with those which occur in Sumatra, Java, the Moluccas, Japan, Kamtchatka, and the Archipelagoes of the Pacific, and with many of the volcanoes of the Cordilleras.

The general phenomena of a violent eruption are illustrated by the accompanying diagram (fig. 47), which is an ideal section of a volcano in action. The pipe or funnel communicating with the interior of the earth is shown at *a*, and the central depression or *crater* at the summit of the mountain, at *b b*. Lava (represented as occupying the pipe *a*) is highly charged with steam or water-gas and other vapours, and these, as the molten matter surges up in the pipe, continually escape from its surface with violent explosions,

and rise in globular clouds, *d d*, to a certain height, after which they dilate into a dark turbid cloud, *c*. From this cloud showers of rain, *e*, are frequently discharged. Large and small portions of the lava are shot upwards as the imprisoned water-gas explodes and makes its escape, forming a fiery fountain of liquid and incandescent drops and fragments, and, along with these, pieces of the rocks forming the walls of the crater and the funnel are also violently discharged; the cooled *bombs*, angular blocks, and *lapilli*, as the smaller stones are called, falling back in showers, *f*, upon

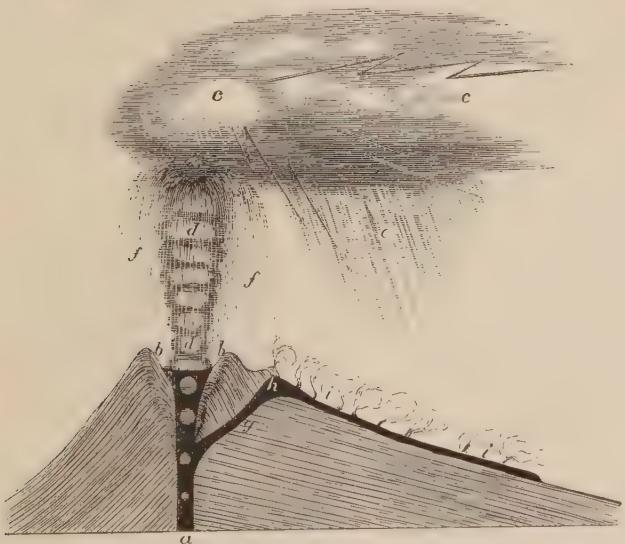


Fig. 47.—DIAGRAMMATIC SECTION OF A VOLCANO IN ACTION.

the exterior parts of the cone or into the crater, from which they are again and again ejected. Forked lightning, probably induced by the intense friction consequent on the rapid escape of steam, often plays round the borders of the dark cloud. The lava at last bubbles over and flows away in torrents. The flow may take place from the lip of the crater or from a fissure in the side of the mountain; or the great hydrostatic pressure of the mass may suffice to rupture the walls of the crater, and the lava then escapes through the breach. In some cases it issues from beneath the base of the cone. In the diagram it is shown as issuing by a lateral fissure, *g*, and streaming down the external slope, with jets of steam and other vapours escaping from almost every part of its surface.

The outflow of lava marks the crisis of the eruption, and after a final ejection of stones and dust the volcano relapses into a quiescent state. Occasionally no lava-flow may accompany an eruption, while in other cases lava greatly predominates. In some paroxysmal eruptions the liquid lava is entirely blown out in the form of dust by one or more tremendous explosions.

II.—VOLCANIC PRODUCTS.

1. Lava.—Any rock ejected in a state of fusion from a volcanic orifice is called a lava. LIQUIDITY.—There are great differences in the liquidity of lavas, such differences appearing to depend on the composition and temperature of the materials.[1] Thus, *basic* lavas —that is, lavas containing a large proportion of lime, magnesia, and iron, and relatively little silica—are more liquid than *acidic* lavas,—that is, lavas which are rich in silica and poor in the bases just mentioned. Hence lavas of the former kind flow as a rule to much greater distances, and often preserve a wonderfully uniform thickness over wide areas; while acidic lavas not infrequently consolidate immediately round the orifice of eruption. STRUCTURE AND TEXTURE.—Lava when it issues from a volcano rapidly acquires a superficial crust, the thickness of which varies according to the character of the lava. Occasionally the crust is smooth and shows a glazed surface, curiously marked with ropy-like foldings and wrinklings. Some very glutinous lavas are drawn out into fine filaments as portions are tossed into the air by the escaping steam; or their surfaces become diversified with little domes, ridges, pillars, or "petrified fountains," formed by jets and driblets of liquid lava, spirted up, in like manner, by steam. But most modern lavas are invested with very irregular and cindery-like or scoriaceous crusts. Towards the surface of a flow where the pressure diminishes, the imprisoned steam tends to expand and segregate into bubbles, that push the molten rock aside, and thus give rise to cavities in the lava, which vary in size from mere points up to large cavernous hollows. So numerous are these vesicles in some kinds of lava

[1] As might be supposed it is difficult to experiment on the temperature of lava. Experiments by Humphry Davy, James, Scacchi and Deville, Silvestri, and others, give various results. Thus the Vesuvian lava of 1794 after it had reached Torre del Greco retained a temperature sufficient to melt glass and silver (about 1870° F.) but not copper. The lava of 1819 fused wires of silver but not of copper; that of 1843 melted silver, and softened copper and iron. Again the lava that flowed from Ætna in 1865 fused copper and softened but did not fuse iron. The fusing point of copper is about 2000° F., and Silvestri was of opinion that the temperature of that last-named lava lay between 1250° and 1500° C. = 2282° and 2732° F.

that fragments of the rock readily float in water. The cavities are often flattened or drawn out in the direction of flow, but this is best seen in the more solid part of the lava that immediately underlies the slaggy crust. During the forward motion of a lava its crust is shivered and shattered into fragments of all shapes and sizes, forming a forbidding and confused jumble of great masses of slag and smaller slabs of cinders or clinkers that roll down the terminal front of the lava, where they accumulate so as to form a kind of volcanic moraine. The upper portion of this heap of clinkers is pushed forward bodily by the fluid lava, while the fragments lying at the bottom, retarded by irregularities of the ground, eventually become involved in the liquid stream, and form a kind of rough pavement over which the lava advances. Thus a section of a typical modern lava-flow shows three portions :—(1) An upper scoriaceous slaggy crust, with a glassy or crypto-crystalline texture ; (2) a middle less porous and often dense portion, having

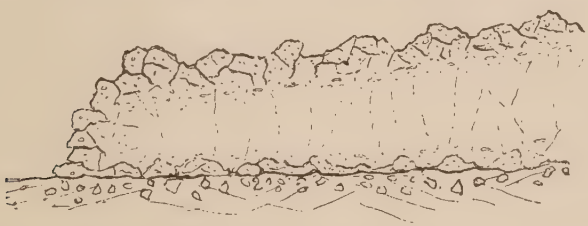


Fig. 48.—SECTION OF LAVA-FLOW.

a more or less distinctly crystalline texture ; and (3) a lower slaggy and scoriaceous part, with a texture resembling that of the superficial crust. The differences in texture are due to differences in the rate of cooling. Towards the top the lava parts with its heat most rapidly, and hence crystallisation is arrested ; and the same must be the case to some extent towards the bottom where the lava is cooled by coming in contact with the ground. But much of this bottom portion, as we have seen, originally formed a superficial crust. Towards the middle of the lava-flow the rate of cooling is much slower, so that crystallisation has time to develop. Now and again some lavas assume a brecciated appearance, as if they were built up of angular fragments. This structure arises from the manner in which the scoriaceous crust breaks up into fragments, which sink down into the underlying fluid or pasty portion, where they become embedded when the rock finally solidifies. But the lava that rises in the throat of a volcano is not always poured out at the surface. Sometimes it consolidates in the funnel—thus

plugging up the vent—and frequently portions of it are forced into cracks and fissures, where they necessarily cool and harden under considerable pressure, forming what are called *dykes*. The structure of the lava thus consolidated under pressure differs from that of a flow in the absence of any cindery-like or scoriaceous crust. It is

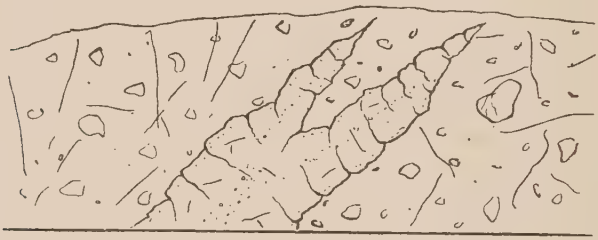


Fig. 49.—DYKE TRAVERSING AGGLOMERATE.

generally fine-grained, compact, or crypto-crystalline towards the sides—its surface sometimes being coated with a skin of glass—while towards the centre it becomes more or less distinctly crystalline. In this central portion, also, steam-vesicles, generally globular in form, are often developed, and not infrequently globular vesicles of smaller size appear in the compact rock at a short distance from the walls of the crevice (fig. 49). In very thick dykes the rock is often extremely coarse-grained in the middle, while in very thin dykes the lava may be crypto-crystalline throughout.

2. Fragmentary Ejectamenta.—The loose materials discharged during eruptions consist of dust and sand, and stones and blocks of all shapes and sizes. DUST.—The finer ash-like dust and comminuted matter is derived partly from the trituration of the ejected stones and blocks, which return again and again to the crater only to be again expelled, and partly from the destruction and dispersion of the molten lava occupying the crater by the explosion of its imprisoned steam or water-gas. The finer volcanic dusts consist principally of minute fragments of glass, with some admixture of volcanic minerals. During paroxysmal eruptions dust is often shot up to a great height and becomes dispersed over very wide areas; and it has been observed that the volcanic minerals in such dust, always in a minority from the first, become rarer the farther the dust is traced from the point of eruption. This arises from the fact that those minerals have a higher specific gravity than the more abundant vitreous fragments, and, as MM. Murray and Renard remark, become sorted out by the winds in their passage through the atmosphere. The coarser dust that falls in the im-

mediate neighbourhood of a volcano is often called *volcanic sand.* Lapilli and Blocks.—Such volcanic sands are often commingled with large and small sub-angular fragments of lava; indeed all gradations are met with—from sand and grit containing few or no stones up to accumulations of angular and somewhat rounded fragments and masses of lava, many of which are porous, scoriaceous, and slaggy (*pumice, scoriæ*). Bombs.—Frequently portions of the molten lava lying in the crater are rent and torn away by the exploding steam and discharged continuously into the air, where they present the appearance of a fiery fountain. Such fragments, having a rotatory motion, acquire a circular, elliptical, or oval form, often resembling pears in shape. They vary from a few inches to a foot or two in diameter, bombs of less than six inches in diameter being more common, as a rule, than those of larger size. Sometimes they are hollow, consisting of a mere shell, as is frequently the case in the recent volcanic tracts of Iceland. Even when they are solid the central portion is usually more or less cellular and porous, while towards the outside they become close-grained and compact, and sometimes show a glazed or glassy external surface. This structure is doubtless due to centrifugal force, which, by relieving the pressure towards the centre, allows the imprisoned steam to expand and segregate; the more compact character of the external part being the result of rapid cooling.[1]

3. Gases, Vapours, and Sublimations.—By far the most abundant of all the gases and vapours discharged from a volcano is steam or water-gas. Lava, as we have seen, is saturated with it to such an extent that many geologists are inclined to believe that it is the energy of this interstitial steam which forces the lava up from the interior and compels it to overflow at the surface. During eruptions it rushes out continuously, or in sudden belches, from cracks and crevices and fissures, in all directions, and rises from the surface of the lava in the crater in large globular volumes, which rapidly succeed each other until eventually they dilate above into a vast canopy of rolling clouds. After the eruption of Vesuvius in in 1855 vapour continued for more than a year to issue in large volumes. Cavalleri, who visited the cone towards the close of 1856, calculated that the amount of vapour issuing from the principal orifice was equal to 516,500 kilogrammes of water per minute; and he estimated that during the eighteen months the volcano had remained in that state the vapour emitted was equal to about 407 millions of cubic metres of water, a quantity which would form a

[1] The bombs of Vesuvius are noted for the variety and abundance of their minerals, such as pyroxene, amphibole, leucite, mica, microsommite, sodalite, garnet, glassy felspar, and idocrase.

lake covering an area of $6\frac{1}{3}$ square kilometres to a depth of 10 metres. The steam discharged in this manner condenses and falls in copious showers, which often give rise to destructive torrents. In many cases this water is increased by that derived from melting snows, and occasionally the torrents are still further swelled by the bursting of subterranean reservoirs, or by the discharge of water from crater-lakes. Very often the floods arising from these various causes are more dreaded than either the falling dust and stones or the flowing lava. Sweeping down the slopes of the mountain the water carries along with it coarse and fine débris, and when it arrives at lower levels it often flows forward for many miles, not as a mere muddy torrent of water, but as a great inundation of soft pasty mud, in which plant and animal remains may be caught up and entombed. Such muds are called *mud-lavas*. When they have consolidated they form fine-grained *tuff*. Now and again mud-lavas are discharged directly from volcanoes, as, for example, in Java and South America.

Many other gases are given off during eruptions, and these, along with steam, continue to escape long after an eruption has ceased. The steam and gases which proceed from the cracks and crevices of a lava-flow form what are called *fumaroles*. In these chlorine and fluorine emanations predominate, while the heat is most excessive ; but as this diminishes they are succeeded by sulphurous gases, the final emanations being usually carbonic acid. After a volcano has ceased to be active it passes into what is called the *solfatara stage*. Lava and loose scoriæ and stones are now no longer ejected, but steam and other vapours may continue to be evolved for centuries. The lips and sides of the various fissures frequently become coated with chemical bodies, such as chlorides of sodium, iron, copper, lead, etc. ; sulphates and borates of the alkalies and alkaline earths ; sulphur and other substances. Some of these substances are merely sublimations, the materials being deposited as the vapours become cooled in their passage to the surface. Others, again, result from the mutual reaction of the gases and vapours. The rocks subjected to the influence of these gaseous matters are often highly affected, lavas and tuffs being frequently converted into mere soft clay-like and chalk-like masses. Thus at Krisuvik in Iceland the palagonite-tuff and lava, from which the hot sulphurous vapours (*suffioni*) proceed, have been converted into white and parti-coloured clays, and loose pulverulent silica, stained with iron and copper compounds. In some districts, where volcanic action has apparently been for a long time dormant, the gaseous emanations consist of carbonic acid (*moffette*), which may proceed either directly from crevices in the rocks or bubble up in thermal and cold springs.

4. Hot and Mineral Springs.—These are of common occurrence in volcanic regions, being most abundantly developed where the igneous forces have become dormant. Among the most remarkable are those eruptive fountains of hot water and steam called *geysers* in Iceland, a name which is now applied to similar fountains elsewhere, as those of New Zealand, the Yellowstone (N. America), Thibet, and Azores. In Iceland, as in other volcanic regions, we meet with all kinds of hot springs, some of these being mere wells and gushings of thermal water, others pools of boiling water, while a few are true geysers. Again, while the water in many is apparently clear and sparkling, in some it is turbid and discoloured, and now and again so thick is it with unctuous sticky mud as to resemble a kind of dirty porridge, bubbling and sputtering as it boils. The water of hot springs, even when clear and bright (which is very commonly the case), is rarely quite colourless. Tints of blue and green predominate, but some springs are tinged yellow and red. The mineral matters held in solution in geysers are many and various, among these being sodium chloride, sodium sulphate, calcium sulphate, calcium carbonate, magnesium carbonate, ammonium carbonate, potassium chloride, silica, various silicates, sulphur, ferric oxide, aluminium oxide, carbonic acid, etc. Some of these substances are deposited on the evaporation of the water containing them, and give rise often to very considerable accumulations. Thus many geysers have built up cones and mounds of calcareous or siliceous matter, as the case may be, in the centre of which is the basin-shaped hollow from which the eruptions proceed. The most common precipitate from the waters of geysers seems to be silica, which forms the substance called *siliceous sinter* or *geyserite.* Sometimes this sinter occurs as a compact, dull, and occasionally translucent substance, in the form of laminæ or thin layers, at other times it is shapeless and more or less spongy or porous in texture ; or it may accumulate in irregular aggregations, resembling bunches of cauliflower or patches of mushrooms, or heaps of smooth rounded accretions, showing a concentric structure. It is usually white or grey, but is not unfrequently stained some shade of red with ferric oxide. In New Zealand, at Whakarewarewa, a geyser has formed a cone of siliceous sinter 100 feet in diameter and 15 feet high. The cone of the Great Geyser in Iceland is 12 feet high, and measures 101 yards by 75 yards in breadth at the base. In the Yellowstone region one geyser-cone measures 12 feet in height, with a diameter of 20 feet at top and a circumference of 120 feet at the base. This cone rests on a platform of siliceous sinter, measuring 75 feet by 100 feet, and is 3 feet in height; while cone and platform together repose upon a mound of similar accumulations that rises 40 feet

above the level of the adjacent Fire Hole River, and covers about $3\frac{1}{2}$ acres.

Several theories have been advanced to explain the origin of geysers by Sir J. Herschel, Krug von Nidda, and Sir G. Mackenzie, Bischof, Bunsen, and Descloizeaux, the view entertained by the two latter chemists being that which has obtained most favour. According to them the temperature in the tube of the Great Geyser increases downwards from the surface, where it is 212° F., to a degree far above that at which water boils under the ordinary pressure of the atmosphere—the water being kept in the fluid state by the weight of the column of water above. They suppose that the water in the central tube communicates by some lateral channel with some space or area which is subjected directly to the action of the source of the subterranean heat. At a point low down in the tube, where the temperature exceeds that of the boiling-point due to the pressure, steam is generated, and forthwith rises into the cooler water above, where it is condensed. In this way the water in the upper part of the tube gets heated and eventually boils, and the pressure on the column below being thus relieved some of the superheated water flashes into steam. This change passes down the pipe, and, successive explosions of steam following close upon each other, the whole contents are shot high into the air—an eruptive fountain of hot water.

Although thermal springs frequently occur in regions of active or extinct volcanoes, they are yet met with now and again in non-volcanic districts. This seems to be more particularly the case in regions where enormous thicknesses of rock have been subjected to powerful fracturing, crushing, and compression, as in many mountain-chains. Such crushing and compression would be transformed into heat, and thus the temperature of water circulating through the rocks might be affected, and thermal springs be produced. Many thermal springs, however, doubtless owe their high temperature simply to the great depths from which they rise. For, as we shall afterwards learn, the temperature of the crust increases with the depth, and must at no great distance from the surface much exceed that of boiling water. Thermal springs occur at all elevations, from the sea-level (Island of St. Paul, Indian Ocean) up to 16,000 feet above that level (near Lake Tengri Nor, Thibet).

From ordinary thermal springs siliceous sinter is sometimes precipitated in large amount, but their most important formations are calcareous. *Calcareous tufa* often occurs in thick and widespread accumulations, as at Hammam Meskhoutine in Algiers, where it forms wall-like masses nearly 5000 feet long, over 60 feet high,

and from 30 to 50 feet wide. The more solid kinds of calcareous tufa are called *travertine*, and are often used for building-purposes, as in Rome, where St. Peter's and all the principal edifices are constructed of this substance.

III.—STRUCTURE OF VOLCANIC CONES.

Volcanic cones generally consist of alternations of lava-flows and sheets of fragmentary materials. Many of the smaller cones, however, contain only the latter, while a few are built up exclusively of lava. In the cones of composite formation sometimes lavas and sometimes fragmentary ejectamenta predominate.

1. **Cones formed of Fragmentary Materials only.**—These vary in size from small monticules up to hills reaching a height of 1000 feet. They may consist entirely of volcanic or of non-volcanic materials, or of a mixture of both. Some of the cones that surround the maars or crater-lakes of the Eifel are built up entirely of the débris of non-volcanic rocks, while others contain a

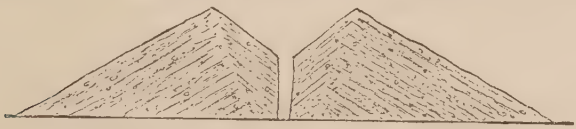


Fig. 50.—SECTION OF TUFF-AND-CINDER CONE.

larger or smaller admixture of volcanic materials. Tuff-and-cinder cones often abound in the neighbourhood of composite volcanoes, as on the slopes of Etna and in Hawaii. Cones consisting of fragmentary materials owe their origin to the discharge of gases and vapours, and may occur on the line of a fissure or fracture, or they may indicate the site of a vertical hole or funnel blown out in the crust. The materials shot out necessarily accumulate round the focus of eruption, where they are heaped up in the form of a cone with a crateral hollow in the centre (fig. 50). The slope of the external and internal sides of such cones varies from 25° to 40°,—corresponding of course to that of the layers of ejectamenta of which they are built up. The slope of the inner sides towards the centre is due partly to the manner in which the ejected material which happened to fall within the rim of the crater would naturally arrange itself; partly also to the action of rain, etc., after the volcano ceased to be active, which would tend to wash down the loose stones, grit, etc., and arrange these in sloping layers. Not infrequently such loose cones are plugged up with a core of lava, which, rising in the throat of the volcano, has consolidated there;

and now and again a single flow of lava has taken place sometimes over the lip, but most commonly through a breach made in the cone by the hydrostatic pressure of the fluid rock.

2. Cones formed of Lava.—These are not common. In

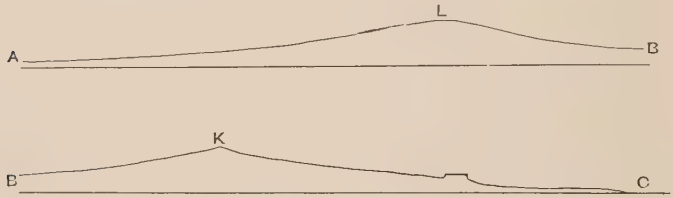


Fig. 51.—SECTIONS OF MAUNA LOA (Dana).

some cases they form abrupt rounded hills or domes, as when they are composed of very viscous lava, which has coagulated and consolidated immediately round the vent. When the lavas are more liquid they usually give rise to low flattened cones, the slopes of which are often very slight. Thus, that of Mauna Loa (Sandwich

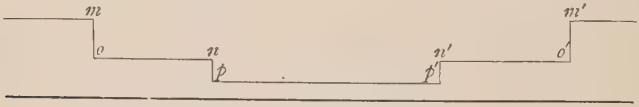


Fig. 52.—SECTION OF CRATER OF KILAUEA, 1840 (Dana).
p p′, Central pit; *o n n′ o′*, lava terraces, 342 ft. above *p p′*; *m m′*, lava terraces 650 ft. above lower terraces.

Islands), spreads out for 20 miles in one direction with a slope of only 1° or 2°. The crater of such a volcano resembles a great quarry excavated in an extensive plain (figs. 51 and 52).

3. Cones formed of Lava and Fragmentary Materials.—Volcanic cones, however, are generally of composite formation—consisting partly of lava and partly of fragmentary materials—but the relative proportion of these constituents varies indefinitely. In many cases where the cone is the result of one considerable eruption fragmentary ejectamenta predominate—the lava appearing only as a single flow. But the cones of most volcanic mountains of any importance are usually built up of a series of lenticular sheets and beds of lava and tuff, inclined outwards in all directions from the crateral hollow. The vertical thickness and extent of the lavas and tuffs are apt to vary; some of the lavas having coagulated upon the steeper slopes, while others have flowed down these slopes and spread often for many miles over the adjacent low grounds. Lavas that flow from the summit of a cone are

not always discharged from the same point, for the form of the crater varies from time to time so as to allow of frequent changes in the direction followed by the molten rock. Again, the distribution of loose ejectamenta is often influenced by the wind, these loose materials tending to be heaped up now on one side and now on another, according to the direction of the aërial currents. The general phenomena of a composite cone are shown in the diagram (fig. 53). Here we have the section of a volcano, the earlier eruptions of which are supposed to have been submarine. The underlying rocks are pierced by the vent which, it will be observed, opened at first upon the bed of the sea. By successive eruptions of lava and loose ejectamenta a cone is eventually formed. The action of marine currents will necessarily tend to sort and sift these loose materials, and should terrigenous sediment be introduced this will become commingled with the ejectamenta; while during pauses in the subterranean activity considerable deposits of non-volcanic materials (*m*), such as ordinary sand or mud, may be laid down upon the tuff. The volcano again becoming active, these terrigenous beds will in their turn be covered up by heaps of ejectamenta or sheets of lava; and this alternation of volcanic accretion and aqueous sedimentation will continue until the cone becomes largely subaërial. Even after that, however, showers of small stones and quantities of sand and dust will be scattered far and wide, and much of this material falling into the sea may be disseminated over vast areas of the sea-bottom. Thus we see how tuffs and tuffaceous terrigenous strata may come to contain marine organic remains. Eventually, after the eruption of many successive lavas and showers of fragmentary materials, a considerable subaërial cone is built up. During paroxysmal eruptions the cone has been frequently shaken, cracked, and fissured by violent explosions. But molten rock has been injected into these cracks and fissures, thus forming a network of *dykes* (*c c*) which no doubt add strength to the volcanic structure. After a great paroxysmal eruption, during which the top of the cone has been blown entirely away, a long period of rest sets in — and the pipe or vent becomes plugged up by lava which consolidates in that position (*b b*). We may suppose that all the lavas of this first stage in the history of our hypothetical volcano are acidic in composition. When, after the lapse of a prolonged period, our volcano again becomes active, the lavas poured out, we may further suppose, are basic. The plug of acidic lava is forced out in whole or in part — a new cone (*e*) begins to grow within the great crateral hollow (*d*), which eventually becomes filled up, and now the basic lavas pour down the outer slopes of the older cone. But after a few eruptions

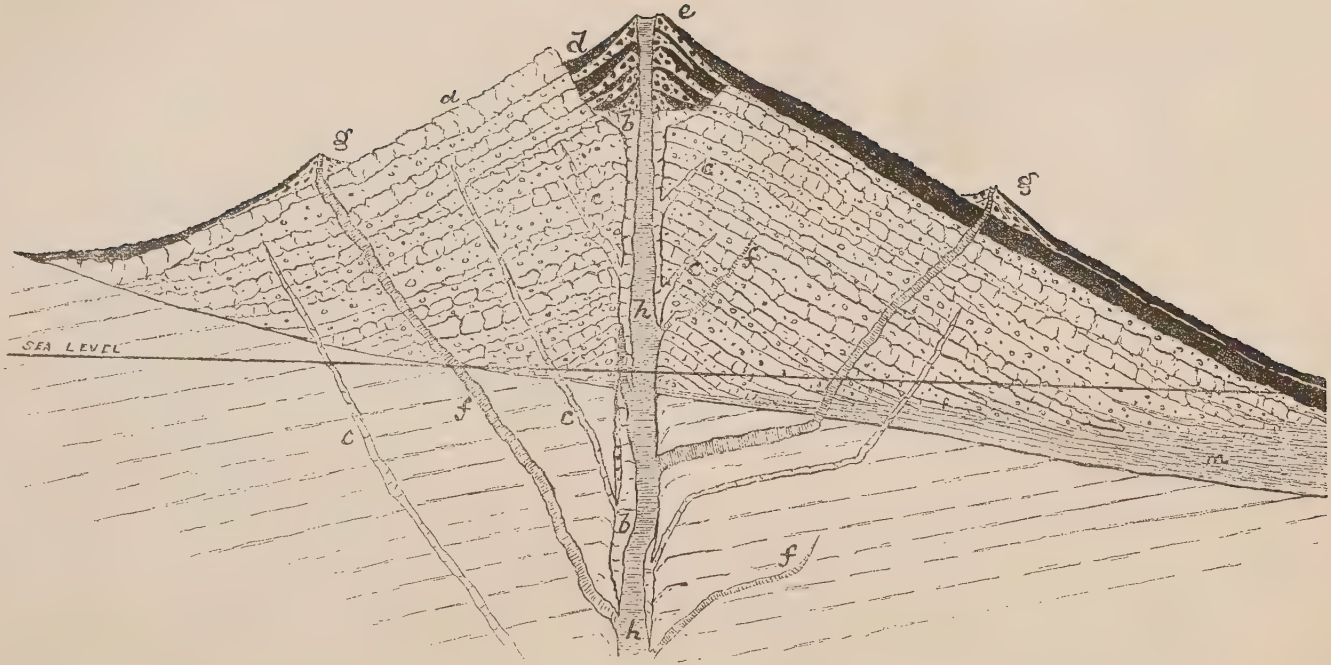


Fig. 53.—DIAGRAMMATIC SECTION OF A VOLCANO, SHOWING PRODUCTS OF TWO PERIODS OF ERUPTION.

a, Old cone of first volcanic period; *b b*, pipe of volcano plugged up with lava; *c c*, dykes of first volcanic period; *d*, crateral hollow filled up with cone (*e*) of second volcanic period; *f f h h*, dykes, and pipes of second period plugged up with lava; *g g*, parasitic cones; *m*, marine deposits interstratified with volcanic materials.

from the summit have taken place, the volcanic forces seem to have spent themselves, lava can no longer be pumped up so high, but makes its escape by lateral fissures at lower levels, forming a number of small parasitic cones (*g g*). Eventually these become dormant or extinct—one after the other dying out, until only steam and gases continue to come from any part of the mountain. Complete extinction follows : the various pipes and feeders becoming choked either with lava or fragmentary materials, or by mere collapse of their walls. It is needless to say that the structure shown in the diagram is only partially exhibited in the crater-walls of existing volcanoes. But, as will be seen in the sequel, many ancient volcanoes in this and other countries have been so worn down and denuded as to afford us abundant hints as to the mode in which composite volcanic cones are built up.

IV.—PETROLOGICAL CHARACTERS OF LAVA.

Most lavas, as we have already seen, are more or less crystalline in structure, although one and the same bed or flow is apt to vary much in texture. There is also considerable variety of texture in separate flows—some being more coarsely crystalline than others. Again, not a few have a close-grained stony texture in which the naked eye fails to detect any crystalline structure, while others appear to be completely vitreous—some resembling dark bottle-glass—some having a greasy lustre like pitch. Yet others have a more or less compact or, as it may be, vitreous base through which are scattered isolated crystalline grains and crystals of various minerals in less or greater abundance. When thin slices of these rocks are examined under the microscope by transmitted light we discover that the rocks which appear to us compact and non-crystalline are yet largely composed of crystalline materials. Even those vitreous varieties which, like some *obsidian*, appear as smooth and devoid of crystalline structure as ordinary bottle-glass, often show scattered crystals of various minerals and numerous little bodies which are believed to be undeveloped or embryo crystals. While coarse-grained lavas, which to the unaided eye seem to be made up entirely of stony and crystalline materials, are shown by the microscope to contain not infrequently some considerable proportion of glass. Now microscopic examination of many crystalline rocks in this and other countries in which no active volcanoes exist or have existed for untold ages, has confirmed geologists in their belief, not only that volcanic action was formerly rife in Britain, but that our ancient lavas are essentially of the same character as those that issue from modern vents. Many of our crystalline igneous rocks,

however, differ in some notable degree from recent lavas. In some cases this difference is due simply to the changes induced by age. The rocks have become more or less altered by the pressure of superincumbent masses, by crushing during earth-movements, or by the chemical action of interstitial water, or by all these causes combined. In other cases, however, the differences cannot be so accounted for, but point unmistakably to the rocks having been consolidated under different conditions.

Fig. 54.—MICROSCOPIC STRUCTURE OF VOLCANIC GLASS: SHOWS HAIR-LIKE MICROLITHS OR TRICHITES.

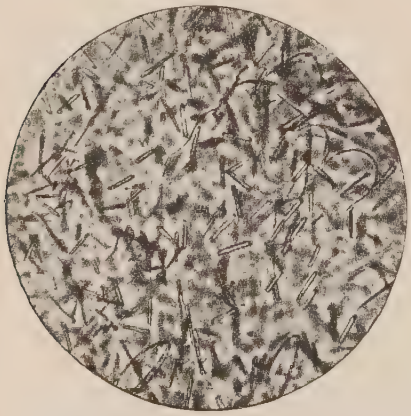


Fig. 55.—MICROSCOPIC STRUCTURE OF VOLCANIC GLASS: SHOWS ROD-LIKE MICROLITHS.

1. Vitreous or Glassy Lavas. — In structure these rocks, as the name implies, are non-crystalline or amorphous. But, as already mentioned, they not infrequently contain large and small crystals, crystalline particles, and minute embryo crystals, which are scattered in less or greater abundance through the glassy matrix or ground-mass. Some of the forms assumed by the minute bodies just referred to are shown in the accompanying figures (figs. 54, 55, 56). They are called *crystallites* and *microliths.* Grouped under *crystallites* come what are believed to be the more elementary forms, representing the first attempts as it were at crystalline arrangement. Like the glass in which they are embedded, they are singly refracting bodies, and they give us no indication as to the nature of the mineral or

minerals into which they might have developed. Microliths are on the whole less embryonic. They are microscopic crystals, imperfectly developed, but often doubly refracting, and by their behaviour, when viewed in polarised light, it is sometimes possible to determine their mineral character. Occasionally well-sized crystals of certain minerals are found to be built up entirely of microliths. Very frequently the crystallites and microliths show a kind of linear arrangement; they appear to be drawn out and arranged with their longer axes in one particular direction, corresponding to the line of flow of the lava: this is called *fluidal* or *fluxion structure*. A characteristic example of this phenomenon is shown in the annexed drawing (fig. 56). In fig. 57 the fluidal structure is shown by the undulating lines and bands of darker glass, which seem to bend themselves round the clear crystals. Another appearance which is seen in many vitreous lavas is known as *spherulitic structure* (fig. 58). Spherulites are minute spherical or ball-shaped concretions which are composed of fine fibres radiating from a centre. *Perlitic structure* (fig. 59) is yet another characteristic feature of some glassy lavas. The rock in this case seems as if made up of little pearly

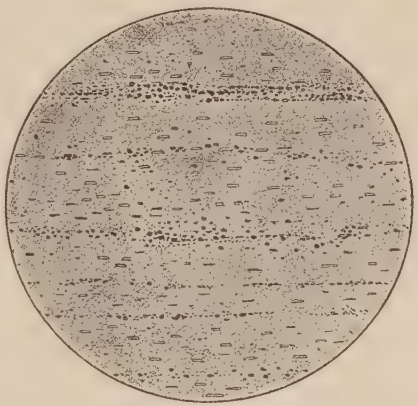


Fig. 56.—MICROSCOPIC STRUCTURE OF VOLCANIC GLASS: CRYSTALLITES AND MICROLITHS ARRANGED IN LINES = *Fluxion structure.*

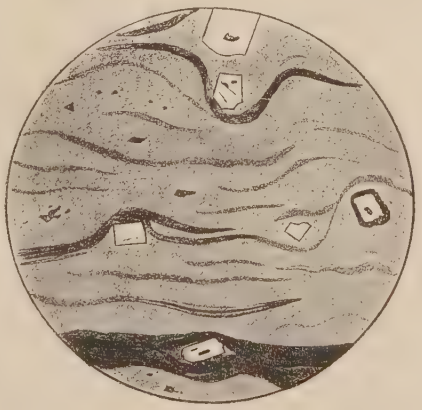


Fig. 57.—MICROSCOPIC STRUCTURE OF VOLCANIC GLASS: LINES AND BANDS OF DARK GLASS SHOW FLUXION STRUCTURE.

or enamel-like globules or spheroids consisting of thin roughly concentric shells. In microscopic sections this *Perlite*, as it is called, usually shows numerous rectilinear or curved cracks, between which the little spheroids appear to be packed.

Fig. 58.—MICROSCOPIC STRUCTURE OF VOLCANIC GLASS: SHOWS SPHERULITIC STRUCTURE.

Fig. 59.—MICROSCOPIC STRUCTURE OF VOLCANIC GLASS: SHOWS PERLITIC STRUCTURE.

2. Crystalline Lavas. — As already remarked, crystalline lavas vary very much in texture. In some the crystalline ingredients are distinctly visible to the naked eye. These are termed *macro-crystalline* or *coarsely crystalline*. Others, again, are so fine in the grain that we can just tell by the eye that they are crystalline, or we may require a pocket lens to make sure. These are *micro-crystalline* or *finely crystalline*. Lastly, there are many that appear to the unaided eye quite compact, and the crystalline character of which can only be determined by microscopic examination. Such rocks are said to be *cryptocrystalline*. Examined in thin slices under the microscope we find that even in the most markedly crystalline lavas there is always a certain amount of amorphous and indistinctly crystalline base in which the macrocrystalline ingredients are set as in a matrix. Here and there this base is clearly of the nature of glass, more or less plentifully charged with crystallites and microliths, and sometimes with spherules (figs. 54 to 58). When such minute bodies are closely

crowded the glassy character becomes obscured, or is completely lost—the base acquiring a *stony* aspect. This *devitrification*, as it is termed, is therefore due to the abundant development of these little bodies—many of which are doubly refracting—and to the presence of minute but more or less perfectly formed crystals of various minerals. Other portions of the fine-grained or compact groundmass of a lava appear under the microscope to be composed of an aggregation of minute crystalline grains and particles of the same mineral nature as the macro-crystalline ingredients of the rock. Thus we may have represented in one and the same rock all stages in the passage from the amorphous to the crystalline condition.

Devitrification is of course not confined to the amorphous groundmass of crystalline lavas, but is often present in recent vitreous flows. In vitreous and crystalline or semi-crystalline lavas alike there is abundant evidence to show that many of the crystals and crystalline grains were formed while the rock was in a liquid condition. The trains of microliths and well-defined crystals seen in fluxion structure recall the appearance of the water-logged sticks and leaves which are immersed in and carried down by rivers in autumn. Sometimes those crystals have a rounded corroded appearance; they are often broken, and not infrequently they contain included portions of the glassy magma which they had caught up during their growth. Indeed it is highly probable that in the case of ordinary lava, the fluid rock, at the moment of its outflow, is far from being in a state of perfect fusion. A large portion of the mass consists of crystals and crystalline particles, the mobility of which is maintained by the amorphous magma of imperfectly-melted matter and steam or water-gas through which they are disseminated. Vitreous lavas were probably in a more complete state of fusion at the time of their eruption. Thus petrologists recognise two stages in the process of solidification of a lava. The first, which may be called the *plutonic* stage, takes place in the interior of the earth (or, it may be, at a great depth in the earth's crust), where the conditions of temperature and pressure must differ very much from those at the surface. It is under such conditions that the larger crystals of many lavas are supposed to have been formed. When the liquid or imperfectly liquid mass rises towards the surface, these crystals are subject to mechanical and chemical changes, induced by the movements of the magma through which they are distributed. Many are thus broken and their fragments become separated, while others are partially remelted, so as to present the rounded and corroded appearance referred to above. The second or *volcanic* stage of solidification

takes place when the lava is poured out at the surface. It is during this final stage that the "ground-mass" solidifies—the ground-mass being composed of smaller crystals and microliths (of the same mineral nature as the larger crystals formed during the first stage), together with non-differentiated vitreous materials.

CHAPTER XII.

MINERALOGICAL COMPOSITION OF VITREOUS AND CRYSTALLINE IGNEOUS ROCKS.

Rock-forming minerals—Essential minerals—Accessory minerals—Secondary minerals and decomposition products—Short notes on the more common minerals occurring in vitreous and crystalline igneous rocks.

Of the several hundred species of minerals which are known only a few are rock-formers, and most of these are met with in crystalline igneous rocks. Some, however, are of much more frequent occurrence than others. Indeed the most commonly occurring mineral ingredients of that group of rocks might almost be counted on the fingers. Rock-forming minerals are generally classed as *essential*, *accessory*, and *secondary;* the *essential* rock-formers being of course the most important. This class comprises those minerals upon whose presence the various species of rocks depend. Thus *granite* is composed of the three minerals quartz, felspar, and mica; each of these is essential. Take away any one of the three and the rock would not be *granite.* The species, however, would not be changed by the addition of such minerals as schorl or garnet. Were these present we should call them *accessory* minerals. And if one or other were very prominent we might describe the rock as a *schorlaceous* or *granatiferous granite.* Essential minerals then, give rise to *species,* while accessory minerals, if sufficiently prominent or remarkable, merely give rise to *varieties.* Many rocks have undergone considerable change since the time of their formation. Sometimes this consists in the mere decay produced by "weathering"—the rock becoming more or less earthy-like and "rotten." Frequently, however, even the freshest-looking igneous rocks when examined carefully are found to have undergone certain changes. Glassy bases are not only devitrified, but are often entirely replaced. The constituent essential and accessory minerals undergo similar changes. Sometimes we see this change only partially effected—the minerals being incompletely altered. At other times the

original minerals have entirely disappeared, and their places have been taken by others. Such replacing minerals necessarily often take the crystalline shape of the original; they are *pseudomorphs*, formed in the moulds of the minerals which they have replaced. Such changes are brought about by percolating water (holding carbonic acid and oxygen, or some salts, in solution), which, acting chemically upon the original ingredients of the rocks, disintegrates these and forms *secondary* minerals, as they are called, out of their constituent elements. Minerals formed in this way are termed *alteration pseudomorphs*. Very often an original mineral has been entirely removed in solution, and subsequently the vacant space has been filled up by the introduction of new mineral matter, forming what is known as a *substitution pseudomorph*. The alterations superinduced in rocks by permeating water are shown not only by the presence of well-defined pseudomorphs, but by that of decomposition-products irregularly diffused through the base, which in many cases is composed of finer-grained matter having the same mineral character as the macro-crystalline ingredients; or they may appear filling up vesicles and other cavities, or lining the joints and cracks of the rock.

Every mineral tends to assume a certain crystalline form, but perfect crystals are rarely met with in igneous rocks. Their growth has been interrupted by that of others adjoining. Even those which have crystallised out first, and which, therefore, had most freedom to develop, are usually imperfect; while those which were last to crystallise not infrequently have no definite shape whatsoever, but merely fill up the interspaces amongst the other minerals. Very often one mineral is enclosed within another—some crystals being occasionally crowded with larger and smaller crystals, or crystalline granules, or microliths of some other mineral species. Such enclosing minerals are termed *perimorphs*, and the enclosed minerals *endomorphs*. Again, many crystals, as we have already seen, may contain inclusions of the ground-mass in which they are embedded, this ground-mass being either vitreous, or stony, or micro-crystalline. Besides such inclusions we meet with minute cavities containing sometimes gases, and sometimes liquids, such as water, liquid carbonic acid, and saline solutions. The fluid cavities are often characterised by the presence of movable bubbles, which are due to the diminished volume of the liquid consequent upon cooling: formerly the liquid must have filled the entire cavity, and the bubble of course represents the vacuity. Sometimes the bubbles are large enough to be seen by the unaided eye, but often a moderately high power is required to detect them. Under a power magnifying from 1500 to 1800 diameters some

fluid inclusions show minute bubbles which have a spontaneous motion resembling the "Brownian movements" in plants.

1. **Essential Minerals.**—The more important essential minerals occurring in crystalline and vitreous igneous rocks are as follows :—

Quartz.	Pyroxene.
Felspar.	Amphibole.
Nepheline.	Mica.
Leucite.	Olivine.

2. **Accessory Minerals.**—All the above-named essential minerals also occur as accessory or adventitious minerals. Besides these it is not necessary to name more than a few members of the class, some of which indeed are occasionally entitled to rank as essential minerals :—

Magnetite.	Titanite (sphene).
Ilmenite.	Hauyne.
Apatite.	Nosean.
Schorl (tourmaline).	Zircon.

3. **Secondary Minerals and Decomposition-Products.**—Amongst minerals of this class the most commonly occurring are Quartz and its varieties, Calcite, Oxides of Iron, Zeolites, Epidote, Chlorite, Serpentine, Steatite, Delessite, Green-earth, etc. Many decomposition-products have an earthy and granular appearance, and often they occur in such minute quantities that we are unable to isolate them for chemical examination, and are therefore uncertain as to what mineral species they belong. For these indeterminate minerals certain provisional names have been adopted. Thus certain greenish scaly or fibrous patches, revealed by the microscope, are termed *Viridite*. Their composition is not known, but they are probably closely related to the hydrated magnesian silicate, serpentine, or to the mineral chlorite. *Opacite* is the name given to black opaque amorphous aggregates, grains, and patches, the precise nature of which is not known ; although that may sometimes be surmised from the chemical character of the known minerals with which opacite is associated. The term *Ferrite* is applied to similar granules and aggregates of a red, yellow, or brown colour, which are probably composed of oxides of iron.

4. **Short Notes on the various minerals mentioned above as entering into the composition of crystalline igneous rocks.**—Quartz.—Hexagonal ;[1] crystallised silica occurs

[1] The crystalline forms assumed by minerals are many and varied, but all are referable to one or other of the following six crystallographic systems :—(1)

as isolated crystals and crystalline granules in quartz-porphyry, and a few other rocks; in granite it has no definite crystalline shape, but merely fills up the spaces between the other crystals. It often contains fluid cavities, which are sometimes so plentiful as to give the crystals a dusty appearance. In microscopic slices the crystals are seen to be usually cracked, but their limits or bounding edges are well defined, there being rarely any trace of alteration, either in the cracks or along the external edges. With ordinary light the mineral is limpid and water-clear, while with polarised light brilliant colours appear, except when the section is extremely thin, or cut at right angles to the vertical axis of the crystal. Quartz is one of the commonest and most abundant of minerals, and is readily recognised by its crystalline form and hardness; it cannot be scratched with a knife, and only a few minerals, and these are not common, are harder. *Chalcedony*, *Agate*, and *Jasper*, are mixtures of crystalline and amorphous silica, which are frequently found lining or filling up cavities and fissures in igneous rocks. Chalcedony also occurs in concentric and radiating globular aggregates of small size in the body of igneous rocks which have undergone more or less alteration.

Felspar.—This is a generic term for a number of minerals which play a very important part as rock-formers in the class of rocks at present under review. These minerals are all essentially silicates of alumina, with variable proportions of silicates of potash, soda, or lime, and they have all much the same hardness, which is less than that of quartz, for they can be scratched with a good knife. They are divided according to their crystallographic characters into two groups, as follows:—

Monoclinic Felspar.	Orthoclase (potash felspar).
Triclinic Felspars	Microcline (potash felspar). Albite (soda felspar). Oligoclase (soda-lime felspar). Andesine (soda-lime felspar). Labradorite (lime-soda felspar). Anorthite (lime felspar).

Owing to the difficulty of distinguishing these felspars from each other in the minute crystals which present themselves in rocks, petrologists have found it convenient to employ one term for the

Cubic or Monometric; (2) Tetragonal or Dimetric; (3) Rhombic or Trimetric; (4) Hexagonal or Rhombohedral; (5) Monoclinic; (6) Triclinic. For a description of these any mineralogical treatise may be consulted.

triclinic felspars, which has reference to what are called the cleavage-planes of the crystals (definite planes along which a mineral tends to split more readily than in other directions). All the felspars have two such cleavage-planes ; but while those of the monoclinic forms are at right angles to one another, the cleavage-planes of the triclinic forms are not at right angles, hence the former are called *Orthoclase* felspars, and the latter *Plagioclase* felspars. As a rule it is not difficult to distinguish between Orthoclase and Plagioclase felspars. A crystal of the latter is usually composed of a number of thin parallel lamellæ, the junction-lines of which show upon the basal cleavage-planes as a series of fine parallel striations, which are visible sometimes to the unaided eye, or with the help of a pocket-lens. The basal cleavage-planes of orthoclase never exhibit such striations. In microscopic slices even very minute crystals of felspar can be differentiated in this way, especially when the slice is seen with polarised light, each alternate lamina being differently coloured. Sometimes, however, plagioclase does not show any striations, and no such narrow parallel stripes or bands of colour can be seen with polarised light. This is specially the case when the felspar is somewhat altered ; so that the absence of parallel striæ is not always a proof that the felspar is not triclinic. *Orthoclase* (potash felspar) as an essential constituent of igneous rocks, occurs generally in imperfect crystals or irregular crystalline aggregates, or as well-developed crystals in certain porphyritic rocks. It is often pinkish in colour. In microscopic slices it rarely appears without some trace of alteration, presenting commonly a turbid, cloudy, or hazy aspect, but in the unaltered and clear portions it usually yields somewhat bright colours with polarised light. It is an essential constituent of several well-known rocks, such as granite, syenite, and some porphyries. *Sanidine* is a clear glassy variety of orthoclase. In microscopic slices it is generally pellucid and water-clear, and the crystals are usually much cracked. It is an essential constituent of many acidic volcanic rocks. *Plagioclase*, as a rock-forming constituent, is of the highest importance. It occurs as well-developed crystals, or in crystalline granules, and also as a very finely crystalline matrix in which other rock-forming species are set. On fresh unweathered faces of a rock the crystals appear as clear glassy-like rods or strips, and the same appearance is revealed in thin slices under the microscope. Plagioclase is an essential constituent of basalt, diorite, and several other well-marked rock-species. The felspar which occurs in rocks containing free silica (quartz), is generally orthoclase, with which sometimes one or other of the more highly silicated plagioclastic felspars may be associated. In

basic igneous rocks, where free silica seldom occurs, the felspars are the more basic varieties of plagioclase—such as labradorite and anorthite.

Nepheline.—Hexagonal ; silicate of alumina, soda, and potash ; generally colourless or white ; occurs as an essential ingredient in phonolite and many modern lavas, in which it seems to play the part of the felspars.

Leucite.—Tetragonal ; silicate of alumina and potash ; grey or white ; an essential constituent of some lavas. In rock-slices leucite generally shows eight-sided sections, but when the crystals are small they have a rounded outline. The mineral is remarkable for its enclosures (glass, or microliths and granules of other minerals), and the symmetrical manner in which they are arranged.

Pyroxene.—Several minerals are included under this term, of which the two most important rock-formers are augite and diallage. They are essentially silicates of lime and magnesia, these bases being often partly replaced by alumina, and oxides of iron and manganese. *Augite* (aluminous lime-magnesia-iron pyroxene), varies in colour, but is generally some shade of brown or green ; frequently it is black. It is an essential constituent of basalt, and occurs in many other crystalline igneous rocks. Sometimes it appears in well-defined stout prisms (as in augite-porphyry), at other times as irregular crystalline granules, and angular or sub-angular aggregates. It shows bright colours with polarised light. The cleavage-planes, which are often indistinct, cross each other nearly at right angles, a character which serves to distinguish it from hornblende (amphibole). *Diallage* (lime-magnesia-iron pyroxene), is a variety of augite, with a foliated structure ; it is generally greenish in colour, and occurs as an essential mineral in gabbro. Augite and diallage crystallise in monoclinic forms. There are other three minerals which may be mentioned here, namely, *Enstatite*, *Hypersthene*, and *Bronzite*, which have the same general composition as pyroxene, but contain no lime ; they crystallise in the rhombic system, from which fact they are sometimes called *Rhombic Pyroxenes*. They occur as essential constituents of the olivine group of rocks.

Amphibole.—This is another general name for a number of minerals which have much the same chemical composition as the pyroxene group ; and crystallise in monoclinic forms. Only one, however (hornblende), is of great importance as a constituent of crystalline igneous rocks. *Hornblende* (aluminous lime-magnesia-iron amphibole) is generally dark-green, brown, or black in colour, occurring often in stout or more slender prisms, or in irregular-shaped angular granules and patches. It is an essential constituent of syenite and diorite, and is met with likewise as an accessory

mineral in many other igneous rocks. Its cleavage is more perfect than that of augite, and often gives the mineral a platy-like structure, the angles between the cleavage-planes being 124° 30′ and 55° 30′.

Mica, like amphibole and pyroxene, is a genus comprising several species of minerals, which, however, greatly resemble each other in several respects. They all crystallise in prismatic forms, and are all equally remarkable for their very perfect cleavage—splitting into extremely thin laminæ or plates, which are flexible and elastic. They differ, however, in composition, which in each case is variable. They are aluminous silicates, with potash, or with magnesia, or other bases; and all contain water. Only two of the species need be mentioned as important constituents of igneous rocks, namely —*Muscovite* and *Biotite*. *Muscovite* (potash mica), has a somewhat pearly lustre, and is usually silvery white, but sometimes brown, yellow, or even green in colour. It is generally the mica which occurs as an essential constituent of granite. As an accessory mineral it is present in many other crystalline igneous rocks. *Biotite* (magnesia mica) is most frequently black or dark brown, but sometimes dark green in colour. It also occurs in granites, but less commonly than muscovite. It is an essential constituent of mica-trap, and is met with as an accessory mineral in many other igneous rocks. In thin rock-slices viewed under the microscope the micas appear as irregular plates, frequently showing a close parallel striation, and having the look of being frayed out or ragged at the ends.

Olivine.—Rhombic; a silicate of magnesia and protoxide of iron; generally green, but sometimes yellowish or brown in colour; occurs as an essential component of basalt and olivine rocks, and as an accessory in several other igneous rocks. In microscopic rock-slices irregular cracks traverse the mineral, which often shows alteration into serpentinous products along those cracks and the boundaries of the crystals or granules. Ferruginous products (hæmatite, etc.) are also frequently met with, replacing some portion of the mineral.

Magnetite.—Cubic; ferrosoferric oxide; black; magnetic; an accessory mineral in a very large number of igneous rocks, in some of which (as in basalt) it is often abundant; in microscopic rock-slices frequently shows square or triangular sections, often, however, occurs in irregular patches and aggregates.

Ilmenite (Titaniferous iron ore); rhombohedral; oxide of iron and titanium; black; a common accessory mineral in basalt and other allied igneous rocks: often altered into a greyish-white substance (leucoxene).

Apatite.—Hexagonal; phosphate of lime with fluoride or chloride of calcium; generally occurs in clear slender prisms and needles penetrating other minerals; is an accessory ingredient in a large number of igneous rocks; seldom shows any alteration, even when the surrounding minerals are decomposed.

Schorl.—Hexagonal; very complicated chemical composition; essentially a silicate of alumina and iron, but contains also a borate; black; occurs as an accessory mineral in long slender prisms or radiating clusters of needles in granite, etc. In thin rock-slices it generally shows a dark greenish colour.

Titanite (Sphene).—Monoclinic; silicate and titanate of lime; not infrequent as an accessory ingredient of granite and some other igneous rocks; in microscopic slices appears yellowish, brownish, or colourless, and the crystals are frequently wedge-shaped.

Hauyne and Nosean.—Cubic; silicates of alumina and soda, hauyne containing, besides, sulphate of lime, and nosean sulphate of soda. These two minerals are so much alike that it is hardly possible to distinguish between them in rock-slices. Nosean appears always to contain minute enclosures of glass, microliths, etc., from which hauyne is occasionally free. Again, hauyne is generally bright blue, while nosean is darker in colour. By some mineralogists they are considered to be only varieties of one species. They occur frequently in phonolite and nepheline-basalt.

Zircon.—Tetragonal; silicate of zirconia; yellow or reddish; occurs as an accessory mineral in some lavas and syenite (zircon-syenite).

Calcite.—Hexagonal (rhombohedral); carbonate of lime; occurs as a secondary mineral in altered igneous rocks; often met with in cells, veins, etc.

Hæmatite (ferric oxide) and Limonite (hydrated ferric oxide) are also frequently met with as pseudomorphs and alteration-products in many igneous rocks.

Zeolites (hydrated silicates of alumina, lime, potash, and soda) occur in the cavities and cracks of many igneous rocks into which they have been introduced by percolating water. They also occur in the body of a rock as alteration-products.

Epidote (silicate of alumina, lime, and peroxide of iron, with some manganese oxide and water); often occurs as a product of the alteration of hornblende and biotite, and of pyroxene, as in basalt-rocks.

Chlorite (hydrous silicate of alumina, ferrous oxide, and magnesia); occurs as an alteration-product of hornblende, etc., in some igneous rocks.

SERPENTINE and STEATITE (hydrated magnesian silicates) are common alteration-products in many igneous rocks; serpentine forms rock-masses which appear generally to have been originally rocks rich in olivine, pyroxene, etc.

DELESSITE and GREEN-EARTH (hydrous silicates of alumina, ferric oxide, ferrous oxide, magnesia, lime, etc.); common as decomposition-products in augitic igneous rocks.

CHAPTER XIII.

PETROLOGICAL CHARACTER OF CRYSTALLINE (INCLUDING VITREOUS) AND FRAGMENTAL IGNEOUS ROCKS.

Descriptive rock-terms—Orthoclase rocks—Plagioclase rocks—Nepheline and Leucite rocks—Olivine rocks—Identity in composition and structure of modern lavas and many old crystalline igneous rocks—Essential difference between modern lavas and a certain class of old crystalline igneous rocks—Fragmental igneous rocks.

BEFORE proceeding to examine the more important groups of crystalline igneous rocks, there are a few descriptive terms which may be briefly defined.

When the mineral ingredients of a crystalline rock have no definite crystalline form, but appear as crystalline granules and scales confusedly commingled, the rock is said to have a *granular* structure. In some igneous rocks the component minerals are occasionally drawn out in wavy or undulating lines, as in the fluxion-structure seen in vitreous lava. In many syenites the crystals of hornblende, and in some trachytes and phonolites the crystals of sanidine, show a similar arrangement. In like manner the vesicles in porous slaggy lavas are often elongated in more or less parallel layers. This structure is described as *streaked*. *Porphyritic* is a term applied to rocks which exhibit well-defined crystals or crystalline granules scattered through a compact or fine-grained base. *Vesicular* and *slaggy* have reference to the pores, cells, and cavities formed by steam in igneous rocks at the time of their eruption; the cavities are often flattened and drawn out in the line of flow. When these vapour-cavities are filled with mineral matter subsequently introduced by percolating water, the rock is said to be *amygdaloidal*, and the kernels of the cells are termed *amygdules*, from their not infrequent resemblance to almonds. Rocks which have the thoroughly crystalline structure of granite are described as *holocrystalline* and *granitoid*. *Massive* is the general term often applied to all crystalline igneous rocks.

The crystalline igneous series comprises a vast variety of rocks,

no thoroughly satisfactory classification of which is at present possible. This arises from the fact that there are often gradations to be observed between one so-called species and another—so that petrological "species" have not as a rule the same value as the "species" of biologists. It is the *primary* or original constituents of a rock which ought to determine its species, but these are often replaced by secondary minerals, and thus it is not in all cases possible to say what were the primary minerals. Moreover, it is probable that in some cases minerals which have been described as *primary* are really *secondary* in their origin. Nevertheless there are many well-marked types of rocks which are readily enough distinguished, and with these we must now make some acquaintance. The rocks to be described are classified as Orthoclase-, Plagioclase-, Nepheline-, Leucite-, and Olivine-bearing, according as one or other of these minerals is a predominating ingredient in their composition.

A.—CRYSTALLINE IGNEOUS ROCKS.

Class I.—Orthoclase Rocks.

Some of these rocks contain much free silica (quartz), while others contain little or none at all; hence they are usually subdivided by petrologists into two groups—(*a*) *Quartziferous*, and (*b*) *Quartzless*. Under the first group comes *Granite*, *Quartz-porphyry*, and *Liparite*, while under the second are ranged *Syenite*, *Quartzless Porphyry* or *Orthoclase-porphyry* and *Trachyte*. But between rocks which are distinctly quartziferous and those in which no quartz can be detected there are intermediate varieties, which serve to show that the division of the orthoclase rocks into two groups is somewhat artificial. For purposes of description it will suffice to arrange them under the heads of (1) *Crystalline*, and (2) *Vitreous*.

1. Crystalline.—Granite.—This is a thoroughly crystalline or crystalline-granular aggregate of quartz, felspar, and mica. The felspar is generally orthoclase (pink or grey), but some plagioclase is often present. The mica may be muscovite or biotite, and other varieties also occur—but the most common, perhaps, is muscovite. There is no matrix or magma in this rock—the several crystals and crystalline granules, confusedly commingled, being bound together by their faces. Some observers, however, state that there is really some trace of an entirely crystalline magma in granite, which is analogous to, although differing greatly from, the magma in which the macroscopic ingredients of a lava are set. In crystallising out the felspar and mica have interfered with each other's

development, so that these minerals rarely assume perfect crystalline forms. The quartz still more rarely appears in the form of perfect crystals, but occurs as irregular crystalline granules, or seems to be moulded upon and hemmed in between the other minerals. Fluid cavities are generally plentiful in the quartz. All varieties of texture are met with among the granites, from very fine-grained up to coarsely crystalline rocks, in which the component crystals may be an inch or more in diameter. The very coarse-grained varieties are called *Pegmatite*. Occasionally the rock is rendered porphyritic by the appearance of large crystals chiefly of orthoclase embedded in a granitoid, or it may be finely-crystalline ground-mass. In the variety known as *Graphic Granite* the quartz is crystallised in the orthoclase, forming alternate zigzag-shaped laminæ which, on a cross-fracture, present the appearance of Hebrew writing. Most granites are traversed by irregular veins, some of which are finer-grained and some coarser than the rock in which they appear. The accessory minerals (such as beryl,[1] topaz,[2] tourmaline, garnet, etc.) are met with chiefly in irregular cavities. Now and again, however, accessory minerals are scattered more or less abundantly through the rock-mass, as is the case with sphene and apatite, small needles of the latter being present in most granites. Many granitoid rocks are ranged under granite as varieties. Amongst these are *Hornblendic Granite*, in which hornblende is added to the other constituents. In this variety the quartz and mica are apt to diminish in quantity when the hornblende is plentiful. When schorl replaces mica we have *Schorlaceous Granite*. *Greisen* is a granular aggregate of quartz and mica. Both schorlaceous granite and greisen are found in veins proceeding from masses of ordinary granite ; and the same is the case with *Aplite*, which is a fine-grained aggregate of quartz and orthoclase only, with sometimes a little mica.

Quartz-porphyry (Quartz-felsite).—In this rock we have a compact ground-mass of felsitic matter, through which are scattered macroscopic or microscopic crystals or crystalline granules of quartz and orthoclase. Many varieties of texture occur. Frequently the rock is markedly porphyritic (*Quartz-porphyry*) ; in other cases the disseminated crystals and granules of quartz and orthoclase are very minute, and the rock has a flinty or hornstone-like aspect (*Felsite*). In the ground-mass of some quartz-porphyries glass has been detected, and now and again such vitreous portions show the spherulitic structure which has been described as of common occurrence in many vitreous lavas. Petrologists are not quite agreed as to the nature of the so-called "felsitic matter" which forms so

[1] Beryl : silicate of beryllia and alumina ; blue, green, yellow, or white.
[2] Topaz : silicate of alumina with a small proportion of fluorine.

large a portion of the ground-mass of quartz-porphyries. In some cases, however, it is resolved under the microscope into a minutely crystalline admixture of quartz and orthoclase; and it seems probable that "micro-felsitic matter" is simply the result of devitrification of a glassy base. The quartz which occurs porphyritically is sometimes in the form of well-defined crystals, but more frequently the crystals are imperfect, and have a corroded appearance. Often it appears as globular blebs or as amorphous granules and lumps, (which, however are probably only corroded double pyramids) and it generally contains many liquid inclusions, and frequently encloses, or partially encloses, portions of the matrix. The orthoclase is generally the most conspicuous ingredient in the highly porphyritic varieties of this rock. As accessory minerals often present in quartz-porphyry, plagioclase, mica, and hornblende may be mentioned. The rock varies in colour, which largely depends upon that of the felspar—red, brown, yellow, and greyish-blue being the common tints. *Elvan* or *Elvanite* is the name given to a crystalline granular rock, composed of quartz and orthoclase, which forms veins associated with granite.

Liparite (Rhyolite, Quartz-trachyte).—The rocks belonging to this group are all highly acidic, that is, they contain a large percentage of silica (70 to 80 per cent). They have a glassy base, often more or less devitrified, and presenting the micro-felsitic aspect so common in the ground-mass of quartz-porphyries. Throughout this glassy or fine-grained felsitic base occur crystals and corroded crystalline granules of quartz, also sanidine, plagioclase, and biotite. Hornblende and augite are occasionally present, while apatite and magnetite often abound. The more compact varieties of liparite are characterised by the presence of spherulitic and fluxion structures, which are often so well developed as to impart a kind of laminated or banded appearance to the rock. Other varieties of texture range from compact and fine-grained up to coarse-grained and granitoid.

Syenite.—This rock is a crystalline-granular aggregate of orthoclase and hornblende, which resembles granite in the absence of any paste or amorphous ground-mass. Syenite is ranked by petrologists amongst the "quartzless orthoclase rocks," but many syenites contain quartz, and plagioclase is also not infrequently present. Besides these accessory minerals may be mentioned sphene, apatite, biotite, zircon, augite, magnetite, ilmenite, etc. The presence of some of these minerals in sufficient quantity gives rise to varieties, such as *Augite-syenite*, *Zircon-syenite*, etc.

Orthoclase-porphyry (Quartzless Porphyry).—This rock-species is a somewhat doubtful one. It has a micro- or crypto-crystalline

ground-mass, through which are disseminated porphyritically crystals of orthoclase and black hornblende, together with some plagioclase and biotite. Quartz, however, is not infrequently present, and the ground-mass now and again shows glassy and devitrified portions, so that "quartzless porphyry" is often hard to distinguish from "quartz-porphyry." *Minette* or *Mica-trap* is a variety containing much mica.

Trachyte.—This rock often resembles in appearance some of the liparites, from which, however, it is macroscopically distinguished by the absence of quartz. It differs also from liparite in the character of its matrix or ground-mass. This, when examined under the microscope, appears seldom to contain any trace of a glassy or felsitic base, but seems in most cases to be made up of a close aggregate of felspar microliths, through which crystals of sanidine and plagioclase, and spiculæ of hornblende or augite, scales of biotite, and magnetite dust, are often more or less plentifully diffused.

Phonolite (Clinkstone) is a greenish grey or brownish compact rock, which has a tendency to split into thick slabs, owing to the parallel arrangement of tabular crystals of sanidine, and emits a marked metallic clink or ringing sound when struck with a hammer. Microscopically, the ground-mass appears composed of microliths of nepheline and plates of sanidine in varying proportions. Augite or hornblende, leucite, and magnetite are usually present, and sometimes nosean or hauyne, sphene, and apatite. The rock is occasionally porphyritic with large tabular crystals of sanidine, prisms of nepheline, green augite, and brown hornblende, and crystals of hauyne. As other accessory minerals may be mentioned biotite and plagioclase; while in joints and cavities zeolites often abound. When leucite is very abundant the rock is sometimes called *Leucite-phonolite*, those varieties in which this mineral appears only in small quantity or not at all being termed *Nepheline-phonolites*.

2. Vitreous.—Pitchstone is a dark-green, reddish-brown, yellow, or sometimes black rock, and occasionally shows a streaked or clouded appearance. It has a pitch-like, oily, or greasy lustre, breaks readily with a conchoidal (shell-like) or splintery fracture, and is translucent on thin edges. Microscopically it is seen to be a true glass, scattered through which are microliths and crystalline grains and crystals of felspar, quartz, biotite, and pyroxene and hornblende. Occasionally spherulitic and perlitic structures may be observed. When macroscopic crystals of sanidine are abundantly developed the rock is called *Pitchstone-porphyry*, the less markedly porphyritic varieties being termed simply *Pitchstone* or *Felsite-pitchstone*.

Obsidian is another natural glass. It is usually black, but brown and greenish varieties occur. Its lustre is markedly vitreous; it breaks with a distinctly conchoidal fracture, and is translucent at the edges. In appearance it resembles bottle-glass. Some obsidians are rendered porphyritic with macroscopic crystals of sanidine; others are often highly vesicular and abundantly charged with spherulites usually arranged in the line of flow. Obsidian is often rich in microliths and crystallites, which are frequently arranged in parallel or wavy lines (fluxion structure). Steam- or vapour-pores of extremely minute size occur in some obsidians in great abundance. The following are structural varieties of vitreous rocks:—

Perlite (*Pearlstone*) is a greyish enamel-like glass, consisting of a mass of mutually adherent globules, composed of a succession of thin concentric shells, and varying from the size of millet seeds up to that of large peas. Examined microscopically perlite is seen to be a true glass, more or less abundantly charged with crystallites and microliths, which frequently show fluxion structure, the streams of microliths, etc., passing through the globules,—from which it may be inferred that the latter are a superinduced structure, probably developed during the cooling of the rock from a state of fusion. In some pearlstones the globules show a fibrous radiating structure (*Spherulitic Perlite*).

Pumice.—This is a frothy-like, cellular, spongiform, and stringy-like rock consisting of glass, which under the microscope shows numerous gas or vapour cavities.

Class II.—Plagioclase Rocks.

Most of the rocks belonging to this class are distinguished by their basic character—that is to say they contain generally less silica than the rocks described under the preceding class. They show every variety of texture from vitreous and compact to coarsely crystalline and granitoid.

Diorite is a crystalline-granular aggregate of plagioclase (generally oligoclase or labradorite) and hornblende—augite and quartz being occasionally present—and there is no recognisable base between the minerals. The hornblende is generally dark green or black, and gives the prevailing tint to the rock. The felspar is white or grey, and sometimes yellow or greenish. Minute needles of apatite may often be detected in microscopic slices, and magnetite, titaniferous iron, and sphene occur not infrequently. Many diorites contain chlorite and epidote, which are probably decomposition-products of the hornblende. Amongst varieties of diorite may

be mentioned *Mica-diorite*, with black or brown mica in addition to the normal constituents; *Aphanite*, a very compact rock, in which the individual ingredients are too minute to be seen; *Diorite-porphyry*, with large crystals of plagioclase and hornblende scattered through a compact or aphanitic base.

Andesite.—The group of rocks described as andesite are grey, reddish, or dark-brown in colour. They show abundant crystals of plagioclase, occasionally accompanied with sanidine, scattered through a base which is usually composed of felspar-microliths, but is sometimes vitreous. Hornblende and augite, one or both, are generally present, but when augite abounds hornblende is not common, and *vice versa*. Magnetite (sometimes abundant, sometimes less so), is likewise invariably an ingredient, scattered through the ground-mass. The crystals of hornblende are often broken, and have blackened borders.

Porphyrite.—Under this head are ranged a number of rocks, some of which appear to be merely altered andesites, and ought properly to be classed with these rocks, while others are closely related to the basalt-rocks. A typical *Porphyrite* consists principally of plagioclase. It shows a crypto-crystalline ground-mass composed of small rod-like crystals of plagioclase with crystalline granules of hornblende, augite, hypersthene, mica, ilmenite, or magnetite. Sometimes traces of a glassy and devitrified base can be detected. Throughout this fine-grained base are scattered porphyritically larger crystals of plagioclase, accompanied often by hornblende, augite, or mica. The basic silicates are frequently much altered. Porphyrites show all varieties of colour, and range in texture from vitreous and crypto-crystalline up to coarsely crystalline. They are often vesicular and amygdaloidal.

Basalt-rocks.—These rocks show considerable varieties of texture, some being vitreous (*Tachylite*, *Hyalomelane*), some compact or crypto-crystalline (*Basalt*), others fine-grained (*Anamesite*), and yet others of a more markedly crystalline structure (*Dolerite*). The basalt-glasses are dark brown or black, and may be thoroughly compact, or spongiform and porous like pumice. The well-known "Pélés hair" of Hawaii consists of basic glass, containing long cylindrical gas cavities. *Basalt* is a black compact rock, with a splintery or conchoidal fracture. Microscopically examined this compact rock resolves itself into small crystals of plagioclase and augite, and generally olivine, and titaniferous iron or magnetite. To these are often added needles of apatite, occasionally nepheline, biotite, and very rarely leucite. The interspaces between these crystals are filled with a vitreous or devitrified base. *Anamesite* is simply a coarse-grained basalt. *Dolerite* is a still coarser crystalline

variety, in which less amorphous base occurs, the base being crowded with crystalline granules of the macroscopic constituents. The olivine crystals are usually broken and rounded and not infrequently blackened at the edges. Basalt-rocks are often vesicular and amygdaloidal. Many are much altered and discoloured with decomposition-products. The olivine is often converted into green serpentinous matter, and the augite is likewise often altered and replaced by secondary products. The glassy base also undergoes change, becoming devitrified, and often assuming a fibrous appearance. Such altered kinds of basalt-rock have been described as if they were true species, *Melaphyre* being the name given to the finer-grained varieties, while the coarser-grained ones are known as *Diabase*. When basalt-rocks are closely associated with coals or carbonaceous shales they often become grey, white, or yellow in colour, and acquire a dull earthy appearance. This is the so-called *White-trap*.

Gabbro is a granitoid aggregate of plagioclase and diallage. The diallage is of a dirty greyish-green or brownish colour, its cleavage-planes showing a kind of pearly or metallic lustre. Apatite and magnetite, or titaniferous iron, are often present in the rock. In some gabbros saussurite[1] occurs in place of plagioclase, and other varieties contain olivine. Gabbro is thus closely related to the basalt-rocks, and is probably only an altered coarsely-crystalline dolerite. *Hypersthenite* comes into the gabbro-group. It is a fine-grained to granitoid aggregate of plagioclase and hypersthene.

Class III.—Nepheline and Leucite Rocks.

Nepheline-basalt is a black compact rock which cannot be distinguished in hand-specimens from plagioclase-basalt. In microscopic slices it appears as a fine-grained aggregate consisting principally of nepheline, augite, and magnetite, with which may be associated leucite and nosean, and a little biotite and apatite. Only meagre traces of a glassy base occur. *Nepheline-dolerite* is a crystalline-granular aggregate of nepheline and augite with some magnetite and apatite, sometimes the nepheline and at other times the augite predominating. Olivine, titanite, nosean, and now and again sanidine may occur as accessory minerals.

Leucite-basalt closely resembles and might readily be mistaken for plagioclase- and nepheline-basalt, the fine-grained varieties being black and compact. In microscopic slices, however, it shows a micro-crystalline ground-mass which contains little or no glass,

[1] An altered form of labradorite: compact, dull, subtranslucent; greyish white, sometimes with a blue, green, or red tinge.

but is composed of leucite, augite, and magnetite, with some olivine and nepheline. A few plates of mica may be present, and occasionally sanidine and plagioclase. The principal minerals are leucite and augite, the rock being greyish when the former, and black when the latter, predominates. *Leucite-porphyry* is the name given to the varieties which are markedly porphyritic with large crystals of leucite (sometimes the size of hazel-nuts), augite, olivine, or hauyne. The lavas of Vesuvius are leucite rocks which differ from leucite-basalt chiefly in the character of the ground-mass, which often contains much glass, and in the more or less abundance of micro- and macro-crystalline sanidine, plagioclase, and nepheline.

Class IV.—Olivine and Serpentine Rocks.

Peridotite.—This name includes a variety of rocks of which olivine is the principal constituent combined with one or more of the following minerals—augite, diallage, bronzite, enstatite, garnet, chrome-iron ore, magnetite, titaniferous iron, and picotite or chrome-spinel.[1] Of these rocks the best-known are *Pikrite*, an augite-olivine peridotite, containing magnetite or ilmenite, and some biotite, hornblende, or apatite, plagioclase being sometimes present; *Olivine-diallage rock*, composed of olivine and diallage; when garnets occur this rock becomes *Garnet-olivine rock*; *Enstatite-peridotite*, consisting of olivine and either enstatite, bronzite, or hypersthene; *Lherzolite*, a granular or fine-grained aggregate of olivine, pyroxene, enstatite, and picotite; *Eulysite*, a mixture of olivine, augite, and garnet; *Dunite*, an aggregate of olivine and chromite.[2] All these rocks show more or less pronounced alteration, many of them acquiring a serpentinous character, and indeed becoming serpentine.

Serpentine is a compact or fine-grained rock, readily scratched with a knife, and showing on a freshly-fractured face a faintly-glimmering lustre. It varies in colour, but some shade of green is commonest, and it is often streaked and irregularly mottled yellow, red, and brown. It is composed principally of the mineral serpentine, through which often ramify veinings of the fibrous variety called chrysotile. Microscopic examination shows that many serpentines are products of the alteration of igneous rocks in which magnesian silicates abound (peridotites). Crystals and granules of olivine more or less serpentinised may be detected in a large number of serpentines, as may also several other minerals which

[1] Aluminate of magnesia with some of the alumina replaced by chromic-oxide.

[2] Chromate of iron, alumina, and magnesia.

are characteristic of peridotites. It is highly probable, therefore, that many serpentines are only extremely altered forms of olivine-rock. Some serpentines, however, may have had another origin (see *postea*).

This general review of the principal characters of massive igneous rocks, must convince us that many of these are true lavas. We have found that a vitreous ground-mass occurs in not a few, that in a still larger number a devitrified base is present, while the not infrequent appearance of vesicular and amygdaloidal cavities affords further proof that we have been dealing with ancient lavas which have consolidated from a state of fusion. It is true that some massive crystalline rocks differ considerably in mineralogical composition from modern lavas, but many of those differences, as we have seen, point to superinduced chemical changes. The rocks have undergone great alteration—some have been, as it were, completely reconstituted ; their mineral matter has been so entirely rearranged that we are pretty much left to conjecture what their original character was ; and between such intense alteration and a condition much resembling that of a recently erupted lava we meet with all stages. It is probable that most of the alterations in igneous rocks have been brought about by the reconstitution of their original ingredients ; sometimes, however, new material may have been introduced by percolating water, just as on the other hand matter may have been carried away in solution by the same agent. There is a certain class of rocks, however, of which granite may be taken as the type, which differ so materially in character from lavas, both ancient and modern, that we are warranted in believing that they never could have consolidated as lava-flows. A study of those rocks in the field, as we shall afterwards learn, shows us that they have in reality consolidated at considerable depths below the surface—they are *plutonic* and not *volcanic* rocks. And the petrological character of granite is quite in keeping with this conclusion. The most infusible of its ingredients (quartz) was the last to crystallise, and this mineral is abundantly charged with liquid cavities. Probably, therefore, the granite consolidated very slowly from a state of hydrothermal fusion. The steam or water-gas which escapes more or less readily from the surface of a lava-flow would be imprisoned in an igneous rock cooling and consolidating at great depths, and its presence diffused through the cooling magma might very well influence the crystallisation of the minerals. In the original highly siliceous magma of granite the felspar and mica first crystallised out—the bases taking up as much silica as they could, and leaving behind a residue of pure silica

which subsequently solidified as a crystallised substance and not as a glass, and became moulded upon the other minerals. Other plutonic rocks often resemble granite in their thoroughly crystalline character and the absence of an amorphous base or magma, so that it holds good as a general rule that igneous rocks which have cooled and consolidated slowly under pressure are more or less crystalline throughout. And this is true of basic and acidic rocks alike.

Glancing over the rock-descriptions given above it will be observed that some rocks contain much more silica than others. Some petrologists, therefore, have classified igneous rocks as *acidic* and *basic*. They have found, however, that there is a large class which cannot be ranked under either head, and for these rocks they have invented another division—*neutral* or *intermediate* rocks. It is of course extremely important to note that some rocks are more acidic than others, but for geological purposes such a classification is useless. If, indeed, it could be shown that those several classes were each of a different age, then the distinctions referred to would be all-important to the geologist. But unfortunately we find that basic, acidic, and intermediate igneous rocks may be associated with almost any geological system. Other petrologists again have sought in their classifications to arrange igneous rocks according to their geological age. But grave difficulties beset all such attempts. Thus, according to some specialists, basalt is of Tertiary and Recent age only. To igneous rocks, which present all the characteristic features of true basalt, but which occur in older formations, they give other names, such as melaphyre and diabase. And they justify this nomenclature by pointing out that the Pre-tertiary rocks referred to contain certain minerals which seldom or never occur in Post-tertiary and Recent basalts. The minerals referred to, however, are *secondary* minerals and *decomposition-products*, and should have no classificatory value. Moreover, there are basalts of Carboniferous age which are just as little altered as any basalt belonging to Post-tertiary times. As well might we attempt to call *siliceous sandstone* by different names according as it occurs in Pre- or Post-tertiary formations. Another classification of igneous rocks is based on the mode of their occurrence—rocks which have been poured out as lava-flows at the surface being termed *volcanic*, while those which have consolidated below that surface are called *plutonic*. But here, again, we are met with the difficulty that many rock-species occur both as plutonic and volcanic rocks, just as amongst the sedimentary class we find *sandstones* of *marine*, *fresh-water*, and *eolian* origin. This classification, however, has more to commend it than the others, inasmuch as it is to a certain extent natural. The subject

however, will be more fully discussed when we come to consider the behaviour and mode of occurrence of igneous rocks in the field.

B.—FRAGMENTAL IGNEOUS ROCKS.

Seeing that massive igneous rocks so frequently assume the character of true lavas we should expect to find that such rocks are now and again accompanied by fragmental accumulations of the same nature as the lapilli and tuffs of modern volcanoes. This is precisely what we do find. These accumulations may or may not be stratified or arranged in beds. Some tuffs consist of rude tumultuous agglomerations of angular and sub-angular blocks; others show traces of bedding; yet others show more distinct traces of water-action in the rounding and smoothing of the stones, and the arrangement of these in more or less well-marked layers and beds. Some again are fine-grained evenly-bedded deposits (now and then containing fossils) which may pass laterally into ordinary sedimentary strata.

Volcanic Breccia: Volcanic Agglomerate.—These rocks are made up of angular and sub-angular blocks, generally unstratified, but now and again showing a rude bedded arrangement. The included stones consist for the most part of fragments of igneous rocks, but commingled with these sedimentary rocks may occur; and some agglomerates of volcanic origin are made up wholly or in large part of non-volcanic materials.

Tuff.—This is the term applied to the finer-grained fragmental matter of volcanic origin, even although much of the material may consist of the comminuted débris of non-volcanic rocks. All varieties of tuff occur from rocks made up of masses of large stones, bombs, and small lapilli, to rocks of the finest-grained and compact character. Not infrequently one and the same bed or mass of tuff may vary indefinitely in texture. Stratification is more or less well-marked in many tuffs, which are often found shading off as it were into ordinary aqueous sedimentary rocks. They are usually distinguished according to the character of their more prominent or abundant ingredients. Thus we have *Basalt-tuff*, *Andesite-tuff*, *Trachyte-tuff*, *Phonolite-tuff*, etc. *Pumice-tuff* is the name given to a rock, rough and harsh to the touch, largely composed of pumiceous débris, and containing fragments of trachyte, scales of mica, and sanidine crystals and garnets. *Trass* is a variety of pumice-tuff, well seen in the neighbourhood of the Laacher See in the Eifel, which contains fragments of pumice, greywacké and shale, basalt, leucite-lava, and crystals of various volcanic minerals, together with

carbonised wood. *Peperino* is a dirty greyish-brown to white earthy granular tuff, containing abundant crystals of mica, leucite, augite, etc., and angular fragments of limestone, basalt, and leucite-porphyry. It occurs in the Alban Hills near Rome. *Palagonite-tuff* is a fine-grained, red, brown, and sometimes greenish and yellow rock, not unlike a mudstone in appearance. In thin slices it is seen to be made up of minute fragments of honey-yellow, brown, and reddish glass, crowded amongst which occur small granules and crystals of augite, olivine, plagioclase, and magnetite. It occurs in Sicily, the Canary Islands, the Faeröe Islands, Iceland, and in Scotland.

Volcanic Conglomerate.—This rock is sometimes composed of volcanic ejectamenta which have subsequently been subjected to the action of water—more or less rounded—and arranged in layers. At other times the rounded stones may have been derived in the same way as those of any ordinary aqueous conglomerate from the disintegration of pre-existing rocks. Volcanic conglomerates of this kind are of course as truly aqueous as a limestone-conglomerate formed out of the débris of limestone; but it is sometimes very difficult to discriminate between a conglomerate consisting of water-worn volcanic lapilli and stones, and one composed of the rounded fragments of igneous rocks which have been broken up by the action of superficial agents. In some cases volcanic conglomerates come partly under both categories, being composed of loose volcanic ejecta, together with débris of lava-form rocks which have been subjected to denudation.

Volcanic Sand, Ash, Dust, Blocks and Lapilli, Bombs, etc. —For an account of these see p. 126.

Volcanic fragmental rocks have often undergone considerable alteration—some of the fine-grained compact tuffs having sometimes assumed a semi-crystalline aspect—so that occasionally they might be mistaken for crystalline igneous rocks. But in such altered tuffs it rarely happens that all the included granules and lapilli are equally altered, and some of these will generally be recognisable, especially on weathered faces of the rock. Where such are not seen it is necessary to examine thin slices under the microscope, when the original fragmental character of the rock becomes apparent. Highly altered and decomposed crystalline igneous rocks have sometimes been mistaken for earthy friable tuffs; but, as a rule, the original crystalline texture is readily detected under the microscope.

CHAPTER XIV.

MOVEMENTS OF THE EARTH'S CRUST.

Earthquakes, general phenomena of; influence of rock-structure in modifying extent, direction, and force of; theory of; effect upon the sea of; geological effects of; origin of—Secular movements of the crust—Evidence of elevation—Evidence of subsidence.

HAVING now assured ourselves that a large proportion of the rocks which enter into the framework of the solid crust of the globe are the products of natural operations which we see going on in the world around us, we have next to ask how those rocks, many of which are of marine origin, have come to occupy their present position. By what means have those ancient sediments been lifted out of the sea and converted into dry land? Now the full answer to this question cannot be given until after we have studied the appearances presented by the rocks themselves in the field. But before doing so it may be well to glance briefly at such evidence as we have of recent movements of the earth's crust. If it can be shown that the distribution of land and sea is subject to change brought about by movements of the earth's crust; if it can be proved that rocks are sometimes shattered, dislocated, and otherwise disturbed, and that the apparently unyielding crust of the globe is yet subject to local and often wide-spread movements of elevation and depression, we shall be prepared to find evidence of such changes in the rock-masses of which our land is built up. And possibly after studying the structure and arrangement of those rocks in the field, we may acquire a more extended knowledge of the nature of earth-movements than we could ever hope to attain were we to confine our attention to such movements of the crust as have taken place within recent times.

I.—EARTHQUAKES.

The tremblings or vibrations which affect the crust of the globe vary much in intensity. Many are so gentle as to pass with little

or no notice; not a few are sufficiently marked to shake down an occasional building and to cause general apprehension of worse results; while some are catastrophic, spreading destruction over wide areas. Earthquakes are felt either as *vertical* shocks, from below upwards, as *horizontal* or *lateral* shocks, or as *undulatory movements*, when the ground seems to rock to and fro like a surging or swelling sea. As illustrating the force of a vertical shock it is related that in 1837 at the fort of San Carlos in Chili a flagstaff, sunk for over 30 feet into the ground and secured with iron rods, was violently shot into the air. Again at Riobamba in 1797, the bodies of many of the inhabitants were projected across the river and fell upon La Culla, a hill over 300 feet in height. During an earthquake which shook Calabria in 1783 the undulatory movement was well marked by the way in which the trees swayed to and fro, their branches touching the ground. In like manner in 1811 it is stated that in Missouri the direction of an earthquake through the forest-lands was signalised by the crashing of the trees. These were seen to swing over violently, and to recover themselves on the passage of the wave—many becoming entangled and interlocked. The area over which an earthquake is felt varies indefinitely. The earthquake of New Granada (1826) was felt over a surface of 750,000 square miles. The earthquake of Lisbon affected an area of not less than 4,000,000 of square miles. It was felt as far north as Britain and Sweden, and south as far as Algiers, Fez, Mequinez, and Morocco. Ships far out on the Atlantic received violent concussions; Barbadoes and the Island of Antigua were affected; and even the remote lakes of Canada suddenly ebbed and flowed. The extent, direction, and force of an earth-wave are necessarily modified by the nature and arrangement of the rocks through which the undulatory movement is propagated. Thus, as the wave passes from a rock of homogeneous character which permits of an equable vibration into deposits consisting of variable incoherent strata of gravel, sand, and mud, the motion will become more or less irregular; and should such incoherent strata occur in considerable thickness at the surface of the ground, the effect of the earthquake will be more destructive over such a surface than over one formed of compact and more homogeneous ingredients. There can be little doubt that joints and lines of dislocation in strata must also affect the transmission of wave-motion through the earth's crust. It has been frequently observed that the great Chilian earthquakes, whose effects are felt for hundreds of miles north and south, are confined to the western foot of the Andes—never being propagated across that chain; and similar facts have been noted in connection with earthquakes in other regions. When we come to consider the

origin of mountains it will be seen that the Andes probably occupy the site of one or more great rectilinear fractures in the earth's crust, which might prevent the propagation of any earthquake movement from west to east across the chain. It may be, however, that the earthquakes which so frequently disturb Chili originate in the Andes; and Mr. Mallet has endeavoured to explain how this might take place without any great disturbance being experienced in the mountains themselves, or in the interior of the continent. If we suppose that the point of origin is immediately under the central part of the chain, it is evident that the wave-motion towards the west will rapidly reach the coast-lands *a* (fig. 60), and the earthquake there will be very severe. The wave which travels in-

Fig. 60.—DIAGRAM SECTION ACROSS SOUTH AMERICA.
1, Pacific; 2, Andes; 3, Atlantic.

land towards the east, however, has a much greater thickness of rock to traverse; and when it emerges at the surface at *b* it may be felt as only a feeble oscillatory movement. In other words the coastlands of Chili are nearest the centre of disturbance.

The observations of Mallet and other physicists lead to the belief that earthquakes are propagated in a series of wave-like motions or undulations. The wave produced by the shock travels outward in all directions in successive spherical shells, the form of which is of course subject to many modifications. Let M a^1 N (fig. 61) be the arc of a circle corresponding to the figure of the terrestrial surface. If a

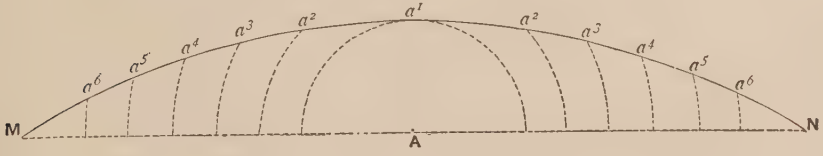


Fig. 61.—DIAGRAM OF EARTHQUAKE, SHOWING EMERGENCE OF WAVES OF ELASTIC COMPRESSION.

shock be produced at A it will be felt as an upward or vertical stroke at a^1; while at a^2, a^3, a^4, a^5, a^6, a horizontal, lateral, or oscillatory motion will be experienced, the motion becoming feebler as the distance from a^1 increases. By observing the direction of the rents in buildings, etc., and the crevasses or cracks opened in

the ground, which will necessarily be more or less perpendicular to the path of emergence of the wave, Mr. Mallet was enabled to estimate the depth from the surface at which the Calabrian earthquake of 1857 originated. By drawing lines (AK, A*l*, A*m*, fig. 62) at right angles to the trend of such rents and fissures (*bc*, *de*, *fg*), it is evident that those lines will converge to a point beneath the epicentre a^1—and this point must be the site of the original impulse A. Contrary, perhaps, to expectation, it has been found that earthquakes originate at no great depth. Mr. Mallet calculated that the impulse of the Calabrian earthquake took place at a depth from the surface of about five and a half miles; and he was of opinion that the focus of disturbance probably never exceeds a depth of 30 geographical miles.

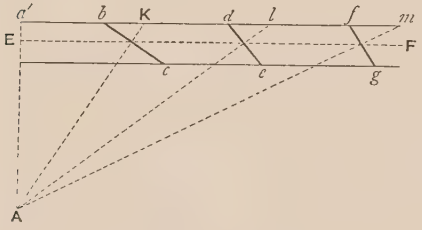


Fig. 62.—DETERMINATION OF THE DEPTH AT WHICH AN EARTHQUAKE ORIGINATES.

The sea is not infrequently affected by earthquakes, some of which originate in the earth's crust under the sea, while others are propagated seawards from the land. There are two kinds of sea-waves which accompany an earthquake—one of which is called the *forced wave*, which is simply the water lifted up on the back of the earthquake wave, and consequently its appearance on the shore is coincident with the arrival of the earth-wave. Later on, however, a much larger wave (the *great sea-wave*) approaches the shore and often rushes far inland with most destructive effect. This great wave of translation is the effect produced by the emergence of the earthquake upon the bed of the sea. The water-wave travels less rapidly than the earth-wave, and is thus last to reach the shore. Noises of various kinds invariably accompany an earthquake—some of which are conducted through the rocks, others travel through the sea, while sound-waves are in like manner transmitted by the air.

When we come to inquire into the cause or causes of earthquakes we are left very much to conjecture. Small local earth-movements may possibly sometimes be due to the sudden falling in of the roof of some subterranean cavity—the work of underground water-action. Again we know that before and during volcanic eruptions, the mountains themselves and the surrounding low-grounds are frequently shaken. Thus the region for fifteen miles round Vesuvius is often shaken by the explosions which take place within the crater.

In like manner all Iceland often trembles while an eruption of Hecla is in progress. Earthquakes, in short, are one of the commonest accompaniments of volcanic activity. It is possible, therefore, that many great earthquakes may in some way or other be the result of the same causes which produce the detonations and tremblings so characteristic of volcanic action. Others again may arise from the sudden snapping of rocks subjected to great strain and tension, such as must take place during the formation of true mountain-chains (see p. 235). At all events it is a noteworthy fact that those belts which are most affected by earthquakes coincide in direction with the axes of great mountain-chains—along the line of which volcanoes occur in less or greater numbers.

The geological effects arising from earthquakes are occasionally of considerable importance. By causing landslips and now and again producing crevasses in the ground, they may interrupt or revolutionise the drainage-system of a country, and thus lead to considerable modifications of surface. But as a rule probably greater changes are the result of the great sea-waves, which attain dimensions surpassing those raised by the greatest storms. Some of those waves have exceeded 80 feet in height. During the great earthquake of 1868, which shook the sea-board of South America from Iburra in Ecuador to Iquique in Peru, it is related that at Arica the great sea-wave carried an American gunboat from her moorings and left it high and dry on the sand-hills, a quarter of a mile from the sea. The terrible destruction produced a few years ago by earthquake-waves in the Straits of Sunda are fresh in our memories ; and the history of many earthquake-haunted regions is full of similar catastrophes. Permanent elevations and depressions of the land are sometimes accompaniments of earthquakes. Thus after the great earthquakes of 1750 the coast of Chili was found to have been permanently raised from three to four feet, the harbour of Conception being laid dry. In like manner the harbour of Nipon in Japan was rendered useless after an earthquake in 1855. Well-known examples of permanent depressions are those of the Runn of Cutch—between the head of the gulf of that name and the mouth of the Indus—and the coast-lands near Chittagong, which were submerged suddenly during the Bengal earthquake of 1762.

II.—SECULAR MOVEMENTS OF THE EARTH'S CRUST.

Besides the elevations and depressions of the surface which have occasionally accompanied earthquakes, there is abundant evidence

to show that vast areas of land have been gradually upheaved and again depressed—there have been frequent oscillations of the level of land and sea. The mere fact that the rock-masses which form the solid lands are composed principally of marine sediments, with now and again intercalations of fresh-water and terrestrial accumulations, is sufficient to demonstrate the truth of this statement. Ever since our land-surface received its present configuration the level of sea and land has continued to change. Some of the evidence bearing upon these mutations may therefore be given here, as it will doubtless aid our conception of those earlier movements to which the solid strata of the globe bear such constant witness.

Evidence of Elevation.—The most striking evidence under this head is that afforded by what are called *Raised Beaches* (fig. 63).

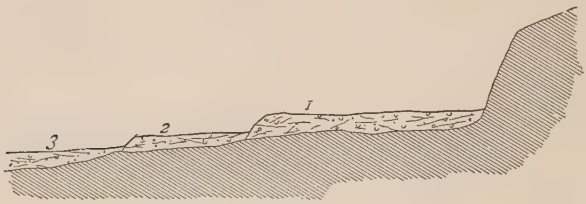


Fig. 63.—RAISED BEACHES.

These are terraces of sand and gravel, often containing shells, etc., and evidently old shore-deposits, which occur in maritime regions at various levels above high-water mark. Sometimes the raised beach consists simply of a horizontal bench or shelf of variable breadth excavated in rock. These beaches and strand-lines frequently terminate inland against a sloping bank or cliff, along the foot of which old sea-worn caves often occur; and occasionally the rocks along such ancient sea-margins are drilled and bored by lithodomous shells, and may even have barnacles adherent to them. The coast-line of Scotland shows a succession of raised beaches, which occur at various levels from 25 or 30 feet up to 100 feet above the sea—those at the lowest level being the freshest and best preserved. In Norway rock-ledges (*strand-linier*) are met with at various levels up to a height of nearly 600 feet; and deposits containing recent sea-shells also occur in many places at similar high levels along the southern part of Scandinavia. The like evidence is met with in the maritime regions of many other lands, as along the coasts of the Baltic, and the western section of the Mediterranean, in Sicily, France, Spain, and the opposite coasts of Africa. Again they occur along the shores of the Red Sea; on the coasts

of Ceylon and Lower India; on the east coast of New Zealand; and along the southern part of the east coast of Asia. The raised beaches of recent geological age which occur on the west coast of South America are remarkable for the height they attain above the sea—reaching a maximum elevation of 1300 feet at Valparaiso. The coast-lands of Central and North America, of Greenland, Spitzbergen, and Siberia furnish us also with many similar proofs of recent elevation of the land.

Evidence of Subsidence.—The best evidence of loss of land is found in the occurrence of submerged land-surfaces. Peat, with buried trees which have grown *in situ*, occurs at many different points along the coast-line of the British Islands and on the opposite shores of the Continent—pointing to a very general loss of land in North-western Europe within recent times. On the coast of New Jersey and North Carolina similar "submarine forests" are met with. Again, it is evident that the fiords of Norway and the sea-lochs of Scotland are simply submerged land-valleys. Similarly many buried river-channels are known to exist in the low grounds of Scotland and England which enter the sea at depths of 100 feet and sometimes of 250 feet below its surface. Indeed, if we could remove the superficial deposits which cover wide areas of Britain, we should find that the sea would reach a great way into the heart of many lowland districts—penetrating sometimes for many miles by such valleys as those of the Clyde, the Ayr, the Tweed, and other rivers. The distribution of existing plants and animals in like manner implies a recent connection of many lands which are now separated by the sea. Thus it is evident that our own islands have received their fauna and flora from the adjacent continent, and in the vast majority of cases our plants and animals could only have immigrated over a land-surface. Finally, if we accept Mr. Darwin's theory of the origin of coral islands, we shall look upon those islands as evidence of a wide-spread subsidence going on over the beds of the Indian and Pacific Oceans.

If we are in doubt as to the cause of many earthquakes we are not less left to conjecture as to the origin of those slow changes in the relative level of land and sea. It is possible that some of the low-level raised beaches in our own and higher latitudes may be due to changes in the level of the sea rather than to actual elevation of the land. It has been suggested, for example, that the thick ice-sheets which covered such wide surfaces of land during the Glacial period may have shifted the earth's centre of gravity, and so caused the sea to rise in the more northerly latitudes. Others, again, have supposed that the ice-masses in question may

have exerted some attraction upon the sea, and drawn the waters upon the land; while yet others have fancied that the weight of the ice-fields may have pressed down the land so as to allow the sea to overflow low-lying maritime regions. It is certainly a noteworthy fact that evidence of great glaciation and submergence go hand in hand in our own and more northerly regions. But even if such causes of change of sea-level were fully established they would not help us to account for the greater submergences to which the higher raised beaches of our own and many other lands throughout the world bear witness. Nor would they explain the great elevations and depressions of which we find such ample evidence in the fossiliferous sedimentary strata which form so large a portion of the solid crust of the globe. No mere oscillation of the sea-level will account for these. They point unmistakably to actual movement of the earth's crust. The consideration of this question, however, must be deferred for the present. When we have studied the appearances presented by rock-masses in the field,—when we have learned something of their structural arrangement we shall be in a better position to consider the various suggestions which have been put forward in explanation of secular earth-movements.

CHAPTER XV.

THE STRUCTURE OF ROCK-MASSES.

Stratification—Beds and laminæ—Contemporaneous erosion—Thinning-out of beds—Grouping of strata—Relation between extent and composition of beds—Lateral changes in beds—False-bedding—Surface-markings—Concretions and concretionary structures—Secretions—Dip, outcrop, and strike—Curvature of strata—Cleavage—Joints—Faults—Unconformity and overlap.

I.—STRATIFICATION.

1. Beds and Laminæ.—From what has been said in preceding chapters as to the origin of rocks, the student has already learned that very many of these show a *bedded arrangement.* They are arranged in *strata*, and hence are said to be *stratified.* This is the case particularly with all those rock-masses which have been laid down as aqueous sediments in lakes, estuaries, or the sea. A stratified arrangement is likewise frequently characteristic of volcanic rocks—consisting, as these often do, of successive sheets of lava and inter-stratified beds of fragmental materials or tuff. The thickness of individual beds or strata may vary indefinitely from a few inches up to many feet or even yards—so that sometimes the *planes of bedding* or *stratification* are close together, and at other times wide apart. Hence we speak of thin-bedded and thick-bedded strata. Now, the individual beds which are separated by planes of bedding are sometimes massive or homogeneous, like that form of sandstone called *liver-rock*, but usually they show more or less distinct traces of gradual sedimentation; that is to say, they consist of a succession of layers which are often conspicuous in sections or cuttings as lines

Fig. 64.—BEDS AND LAMINÆ.
st st, Beds of sandstone; *sh sh*, beds of shale, showing lines of lamination, *l*; *p p*, planes of bedding.

running through the bed in the same direction as the lines formed by the planes of bedding (fig. 64). Frequently the layers composing a bed are of extreme thinness, as in *shale*, and they are then termed laminæ, while the bed itself is said to be *laminated*. As a rule, planes of bedding (or the lines that seem when seen in section to separate a group of strata into successive beds) are more strongly marked than planes or lines of lamination. This arises from the fact that while planes of bedding very often separate rocks of differing petrological character, planes of lamination occur in one and the same rock-bed. No long time may have elapsed between the deposition of successive laminæ; probably in very many cases a lamina had not time to become consolidated before another was deposited above it; and afterwards when the bed hardened the laminæ would become more or less adherent. But in the case of separate beds, especially when these are composed of different materials, some considerable time must have elapsed between the accumulation of the successive strata. If, for example, we met with a section showing the following arrangement of beds:—

(3) Shale,
(2) Limestone,
(1) Shale,

we should reasonably infer that the bedding-planes represented pauses in the accumulation of the series. The lowest bed of shale (1) we should infer was laid down in somewhat quiet water. Now, the limestone (2) largely made up, as we shall suppose, of corals and other marine organisms, betokens the presence of clear water. Some physical change which arrested the deposition of mud and silt over the same area must have taken place. Either the current or currents which brought it were diverted in some other direction, or the bed of the sea had subsided to a depth beyond the reach of any copious and continuous supply of terrigenous materials. Anyhow, a pause ensued, and then commenced the formation of the limestone by the gradual accumulation of the exuviæ and skeletons of marine organisms. The presence of the shale (3) overlying the limestone, in like manner indicates a pause,—pointing, as in the former case, to a change of physical conditions,—to a return, in short, of the conditions which marked the deposition of the lower shale (1). Of course we cannot tell what lapse of time is represented by such changes in a succession of strata. Doubtless the pauses represented by bedding-planes were of very unequal length; some probably do not point to any longer interval than that which intervened between the accumulation of successive laminæ in a shale; while others, again, may represent a longer lapse of time than was required for the deposition of the strata themselves.

2. Contemporaneous Erosion.—That the succession of various beds in a group of strata has sometimes been brought about by changes in the direction or the force of currents is shown by the phenomena of contemporaneous erosion. In the following section

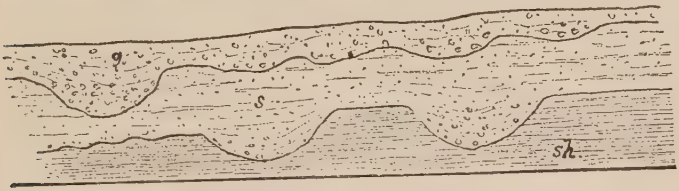


Fig. 65.—CONTEMPORANEOUS EROSION.
sh, Shale; *s*, sandstone (sand); *g*, coarse gravel and shingle.

(fig. 65) for example, we have a set of sandstones and shales. At the bottom of the section are seen shales showing an uneven surface, over which occur beds of sandstones and conglomerates—the latter resting upon an uneven surface of the former. Here, then, we have good evidence of changing physical conditions. The shales, we may suppose, were deposited in comparatively quiet water. After some time, however, their accumulation is arrested; stronger currents sweep over the bottom and denude the silts and muds, and by and by coarser-grained sediment (sand) is laid down over the eroded area. By and by a similar change ensues—the sand is denuded and trenched just as the silt was before, and gravel and shingle accumulate over its uneven surface. Such a series of changes might readily take place in the case of estuarine and marine deposits, or opposite the mouth of a river discharging into a lake.

3. Thinning-out of Beds.—The preceding sections show us, then, that planes of bedding usually indicate a pause in the deposition of the strata. This is even more strikingly displayed by the phenomena known as the *thinning-out of beds*. It is obvious that every bed must be more or less lenticular or wedge-shaped. Littoral deposits, as we have seen, thicken towards the shore, and thin-off seawards. Infra-littoral and oceanic accumulations must likewise thicken and thin-out. When we trace sedimentary strata across a country, we are constantly being reminded of their aqueous origin by the way in which individual beds and groups of beds seem to swell out or become attenuated, as the case may be. Thus we may have a series of beds, *a*, *b*, *c*, *d*, several members of which, as we follow the strata, become attenuated and thin-out, so that eventually the complete series may be represented by only one or two of the beds, as *a d*—the strata *b c* having disappeared. In the

annexed section (fig. 66), for example, we have from *a* to *d* an apparently complete and regular succession of four beds superimposed

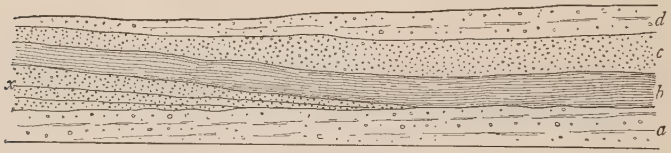


Fig. 66.—THINNING-OUT OF BEDS.
a, Shaly sandstone; *b*, shales; *c*, sandstone; *d*, shaly sandstone; *x*, sandstone beds.

one above another. The bedding-plane between *a* and *b* may be no more strongly marked than that between *b* and *c;* and yet when we trace the same strata in some particular direction we find new strata (*x*) coming in between *a* and *b*, and thickening out till they assume considerable dimensions. Such phenomena, which are of constant occurrence in nature, warn us that a sequence of strata, no matter how regular it may be, is not necessarily complete. The bedding-planes may indicate gaps of greater or less importance.

4. Grouping of Strata.—As we shall see in the sequel, we obtain great aid from fossil organic remains in estimating the relative importance of the gaps which are represented by bedding-planes. But, in the absence of fossils, we can often arrive at some reasonable conclusion, from a consideration of physical evidence alone. We find, for example, that although almost any diversity of strata may occur in a series, yet it is more usual to meet with certain kinds of rocks associated together. Thus, sandstone very frequently alternates with shales, conglomerate with sandstone, limestones with fine shales, and so forth. These associations are readily explained when for conglomerate, sandstone, and shale, we read gravel, sand, and mud; and when for limestone we read calcareous mud. Nothing is more common in terrestrial waters and the sea than alternations of sediment. But as a rule we pass from gravel to grit and sand, and not directly from gravel and shingle to mud. And so in like manner we can see how in deeper water, where marine organisms flourish vigorously, the first terrigenous sediments to gather over the calcareous accumulations forming there will be mud rather than sand and gravel. Thus, in a regular, or, as it is termed, *conformable* sequence of sandstones and shales, we should infer that even although the individual bedding-planes might represent longer or shorter pauses, yet these pauses are not likely to have been very prolonged—the strata indicating, in fact, such minor oscillations or changes of current-action which one

might naturally expect should characterise the deposition of strata during the persistence of certain physical conditions. And so in like manner when we meet with limestones associated with shales, we need not infer that any prolonged interval of time separated the formation of the individual beds. Probably we should find upon examination that towards the top of the limestone that rock became more or less mixed with argillaceous matter, and that the passage from limestone to shale was therefore not necessarily abrupt. In other words, that no long interval occurred between the formation of the beds.

If we are uncertain as to the relative duration of the intervals between the accumulation of successive beds, we are hardly less uncertain as to the time required for the deposition of the beds themselves. Speaking generally, the relative thickness of individual strata is no index to the time taken for their formation. The character of some beds implies more or less rapid accumulation, while the appearances presented by others indicate very gradual growth. Often, however, there is nothing in the beds themselves to help us in determining whether they were rapidly or slowly accumulated. But as we have no reason to suppose that the formation of ancient sedimentary deposits differed from the processes of sedimentation now in progress, we may well believe that beds only a few feet in thickness may sometimes represent a much longer lapse of time than many great successions of strata. Mere thickness, therefore, is no test of the relative time required for the formation of individual beds. Occasionally the trunks of trees, with their roots attached, have been met with standing erect on what appears to have been an ancient soil—the trunks surrounded on all sides by sandstone or other strata. When the beds through which those trunks pass are of aqueous origin, it is evident that the process of sedimentation must have been rapid—the trees were, in fact, buried before they had time to decay and fall. Similarly trunks of drifted trees in a fine state of preservation have been discovered embedded in sandstone—the trunks extending across a considerable thickness of the rock. It is conceivable, however, that in some cases sandstones, which give evidence of such very rapid accumulation, may be partly of the nature of eolian rocks—or blown sands.

5. Relation between the Extent and Composition of Beds.—Strata, as we have seen, are more or less lenticular in shape, and consequently appear to thicken and thin-out when they are traced continuously. This holds true with regard to individual beds and groups of strata, and as a rule we find that there is a more or less close relation between the composition or petrological character of a bed and its extension. Thus coarse-grained deposits

like conglomerate and grit are apt to "die out" rapidly; but fine-grained sandstones and shales tend to be more persistent, while limestones are generally continuous over still wider areas. Groups of strata, in like manner, show similar appearances. A vast succession of limestones, shales, and thin sandstones, for example, will as a rule have a greater horizontal extension than a correspondingly thick group of coarser-grained strata. Examples of this kind will be adduced when we come to consider the subject of historical geology.

6. Lateral changes in the Petrological Character of Rocks.—When we consider that beds are more or less lenticular in shape, it is evident that we may have rocks of very different kinds occurring on one and the same geological horizon. Limestones, sandstones, and shales, lavas and tuffs, must often be strictly contemporaneous. As we trace strata across a country we constantly see some thinning away and their position in the series being occupied by others. So that a thick series of limestones may become split up, as it were, by intercalated beds of shale and sandstone, and these last may eventually come to form the whole thickness of the series to the entire exclusion of any limestone. Sometimes these changes in the lateral range of particular beds are brought about by the simple dove-tailing or interosculation with these of beds having a different character. At other times the change appears in the beds themselves. Conglomerates pass laterally into sandstones; sandstones, becoming more and more argillaceous and finely-divided, pass into shales; shales, again, by the gradual increase of calcareous matter, become marly and eventually pass into limestones. So in like manner we may find coals passing laterally into carbonaceous shales and ironstone, and tuffs shading off into shale or sandstone.

7. False-Bedding: Current-Bedding.—Although it holds generally true that strata have been deposited in approximately horizontal or gently-inclined layers, yet owing to various causes the several layers of which a bed is composed are often inclined to each other at various angles. This is termed *false-bedding*, *current-bedding*, or *diagonal bedding*. Such irregularities are usually due to changes or oscillations in the direction and force of currents, as in the

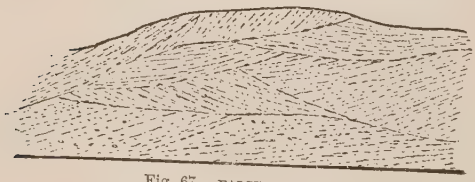


Fig. 67.—FALSE-BEDDING.

annexed section (fig. 67). Similar false-bedding may also occur in sandstones of eolian formation. False bedding, however, must not be confounded with certain confused appearances which are due to other causes. The accompanying section (fig. 68), for example, shows local contortions in beds of laminated clay belonging to the Glacial formation which have probably been caused by the pressure of the ice-sheet underneath which the overlying till or boulder-clay was amassed. In fig. 69 again, the contortions have probably been produced by the grounding of ice-rafts upon a shallow sea-bottom.

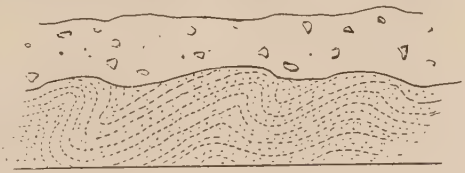


Fig. 68.—CONTORTED BEDS UNDER TILL OR BOULDER CLAY.

Fig. 69.—CONTORTED CLAY AND SAND (PORTOBELLO).

8. Surface-Markings.—The surfaces of some strata exhibit markings of precisely the same character as may be seen upon flat sandy and muddy beaches after the retreat of the tides,—such are the so-called *ripple-marks* or *current-marks*. Such markings are of course also formed upon the beds of rivers and the floor of the sea below low-water mark, and even in water of some little depth; but as the conditions for their formation are most frequently met with in the shallower waters round a coast-line, the frequent occurrence of ripple-mark in a succession of sedimentary beds may often be taken as evidence, so far as it goes, for the formation of the beds under littoral or estuarine conditions. Besides ripple-marks the surfaces of certain beds now and again show *sun-cracks*. These are most commonly met with in a series of thin-bedded flagstones,

argillaceous sandstones and shales, etc. They have evidently been formed in the same way as the fissures which are produced upon the mud-flats of tidal river or estuary by the drying and shrinking of the silt during its temporary exposure at low tide. Similar cracks may be met with on the borders of a lake the level of which is subject to be lowered during the droughts of summer. The cracks are of course filled up by new deposits when the mud-flats are again overflowed. Not infrequently the material filling the cracks is of harder consistency than the rock in which they occur. When the bed overlying the cracks is removed a cast of these often projects from its under-surface, or frequently the casts remain in the moulds so as to form a series of polygonal ridges ramifying over the whole surface of the old mud-flat. *Rain-prints* are the small pits caused by the impact of large drops. They are often deeper at one side than the other, from which we may infer the direction of the wind at the time the rain-drops fell. Ripple-marks, sun-cracks, and rain-prints are often associated in one and the same series of strata, and the evidence they furnish of shallow-water conditions is often abundantly strengthened by the appearance of the tracks and trails of worms, molluscs, crustaceans, birds, and land-animals, and the plentiful occurrence of land-plants, and other indications of the near vicinity of a shore-line—the whole aspect of the strata themselves indicating accumulation in lacustrine or estuarine waters.

9. Concretions and Concretionary Structures.—Many rocks contain nodules, balls, and irregular masses of various kinds, which are evidently of later formation than the beds that hold them. These are called concretions, and owe their origin to the concentration or segregation, round various points, of mineral matter which was formerly diffused through the mass of the rock. They are of various composition and shape. Some are crystalline, such as the gypsum which occurs in many clays; others are more or less spherical, with an internal radiating structure, as iron-pyrites in shales; others, again, are amorphous internally and often fantastically shaped, such as the "fairy-stones" that occur in some clays in this country, and the similar grotesque clay-concretions (Lösspuppen, Lössk indel, or Lössmännchen) which characterise the löss of Germany. In certain clays met with in Southern Norway somewhat similar concretions occur, in many of which are found a fossil shell or a fish. Nodules and balls of clay-ironstone are of very common occurrence in the fireclays and shales of the Coal-measures; in these organic remains not infrequently occur, such as coprolites (fossil excrementa), fish, plants, etc. Many of the nodules are cracked internally, the cracks being widest towards the

centre and dying out towards the circumference, as if the interior portion had contracted after the outside had hardened. The cracks are frequently filled up with some crystallised mineral matter, generally with calcite. Such internally cracked nodules are called *septaria*. Other notable concretions are the nodules and masses of flint which occur in chalk; chert and chalcedony likewise frequently occur in concretions. That such concretions are of later origin than the rocks in which they occur is sometimes shown by the fact that they are traversed by the lines of sedimentation; but in other cases the fine layers of some rocks seem to have been somewhat disturbed by the growth of the concretions.

Rocks themselves now and again assume a concretionary structure. This is well seen in the case of dolomite or magnesian limestone, which often appears to be made up of rounded and spherical masses, through which the lines of bedding pass. Sandstones and shales, and some fine-grained volcanic tuffs, and certain crystalline igneous rocks, also sometimes show concretionary structure, the concretions consisting of concentric coats.

10. **Secretions** are depositions of mineral matter in the cracks and cavities of rocks. They are generally the result of percolating water charged with solutions, which may have been derived from other rocks or from the rock itself in which the secretion is formed. The shape assumed by secretions depends of course upon that of the hollows in which they occur. Very often they consist of concentric coats, sometimes of one and the same, sometimes of various mineral substances, and frequently they are hollow internally, and lined with crystals (*drusy cavities*). The minerals most commonly met with in secretions are quartz and chalcedony, calcite, zeolites, etc. They are well seen in many igneous rocks, the vesicular and slaggy cavities of which are frequently filled with secretions.

II.—INCLINATION OF STRATA.

1. **Dip of Strata.**—Although strata are occasionally met with in the horizontal position in which they were accumulated, yet they are more usually inclined at various angles up to vertical. This inclination is termed the *dip* of the strata, and the point of the compass towards which the strata are inclined is called the *direction* of the dip. The degree of dip is measured by the angle which the beds make with the plane of the horizon.[1] In measur-

[1] The instrument used for measuring the angle of dip is called a *clinometer*. For general purposes it is most convenient to have the clinometer combined with a pocket-compass,—with the latter one takes the *direction* and with the former the *degree* of dip.

ing the dip it is of course essential that we ascertain the true direction of the bedding-planes. We must be sure (1) that the lines which we see traversing the face of a rock-section are really lines of bedding, and (2) that their inclination truly coincides with the full dip ; in other words, we must be certain that the exposed rock-face runs in precisely the same direction as the bedding-planes. This we can usually ascertain by examining the exposed section carefully, for it will rarely happen that some bed does not project a little beyond the others, so as to allow us to see the actual plane of bedding and take its direction and dip by means of compass and clinometer. The student will remember, therefore, that the lines of bedding seen in cliffs and quarries do not necessarily show the direction of the dip. It is evident, indeed, that if a cliff should intersect the strata at right angles to their dip the lines of bedding would appear as horizontal lines (*a*), although the planes of bedding

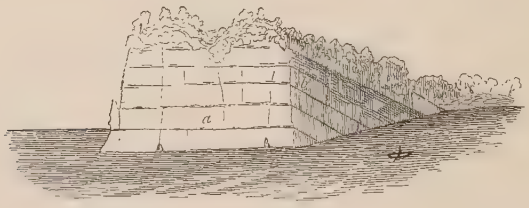


Fig. 70.—DECEPTIVE APPEARANCE OF HORIZONTALITY AT *a* ; DIP SHOWN AT *b*.

might be dipping at a high angle, and either towards or away from the spectator (*b*, fig. 70).

2. Outcrop[1] is the name given to the edges of strata as they appear or crop out at the surface. In the case of horizontal strata it is obvious that the direction or trend of the outcrop must vary with every change in the configuration of the ground. In a country formed of perfectly horizontal strata lines of outcrop will be also contour-lines exhibiting the actual configuration or shape of the ground. The outcrops of inclined strata are regulated partly by the contour of the land and partly by the degree of inclination. Thus gently-inclined strata will have a more sinuous outcrop than strata dipping at a higher angle—the outcrop of the former being most influenced by changes in the configuration of the land. The higher the angle of dip the less influenced is the outcrop by the form of the ground, until, in the case of vertical strata, it becomes independent of land-features, and runs in a straight line.

[1] *Basset* or *basset-edge* is another term occasionally used, but it is seldom met with in geological literature, and chiefly in text-books.

In like manner the width or breadth of an outcrop must necessarily vary with the dip and the form of the surface. Thus beds dipping at a low angle will have a relatively broad outcrop—the outcrop becoming narrower as the inclination increases, until when the strata are vertical the outcrop can as a rule be no wider than the actual thickness of the beds.

3. Strike is a line drawn at right angles to the dip, which can only under exceptional circumstances coincide with the outcrop, as when the strata are vertical or when they crop out on a level surface (fig. 71).

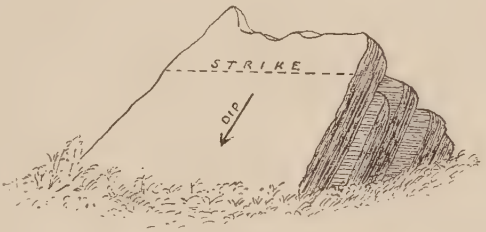


Fig. 71.—DIP AND STRIKE.

4. Curvature of Strata.—Inclined strata are, with few exceptions, the remaining portions of large curves or undulations, the upper portions of which have been removed by denudation. The simplest form of such a curve is that known as a *monoclinal fold*, exhibited in the section (fig. 72). The dotted lines *e e c* represent

Fig. 72.—MONOCLINAL FOLD OF STRATA IN ISLE OF WIGHT. (R.)
The dotted lines above land show the former extension of the strata, since removed by denudation.

the strata which have been removed by denudation. A monoclinal fold is simply an abrupt increase of dip in gently-inclined or approximately horizontal strata, followed by an equally abrupt return to the normal inclination. The term *qua-qua-versal* dip is applied to a series of dome-shaped strata—*i.e.* strata which are inclined outwards in all directions from a central point. The converse arrangement, or pot-shaped depressions, in which the strata are inclined inwards from all directions to a central point, are said to have a *centroclinal* dip. But such dips are only of local occurrence. Strata, as a rule,

are folded along an axis, and such folds are termed *anticlines* when strata dip away on either side from an axis; and *synclines* when they dip in on either side to an axis (figs. 73, 74). Anticlines and synclines

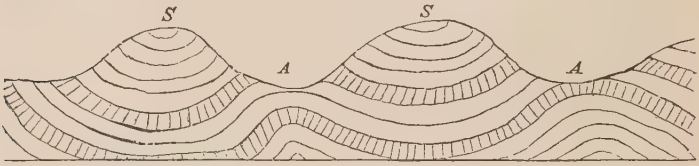


Fig. 73.—ANTICLINES AND SYNCLINES.

usually occur in series. In gently undulating strata they are apt to be irregular—the axis bending now to one side, now to the other, and

Fig. 74.—ANTICLINES AND SYNCLINES. (R.)

often dying off at either end. Arches may flatten out and pass into synclinal troughs, and troughs may disappear by the bending up, as it were, of their axes, and be replaced by horizontal strata or by

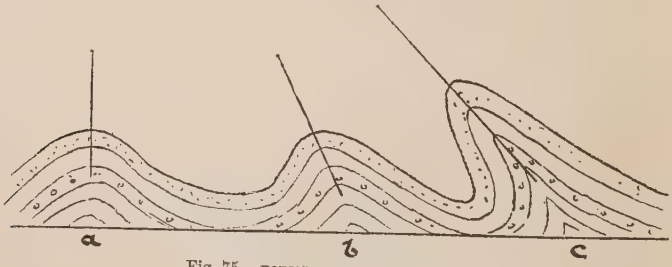


Fig. 75.—FORMS OF ANTICLINAL AXES.
a, Axis vertical; *b*, axis inclined; *c*, axis much inclined.

anticlinal arches. With greater inclinations arches and troughs acquire a more regular character—there is less sinuosity of the

axes, and anticlines and synclines are more persistent. In strata with a moderate dip the strata on opposite sides of an anticlinal

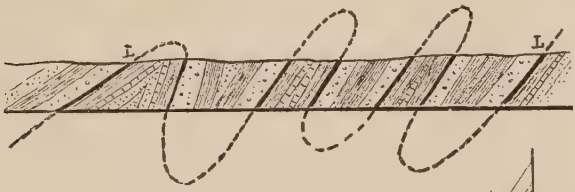


Fig. 76.—ISOCLINAL STRATA.

axis dip at approximately the same angle —the axis in this case being of course *vertical*. But in more steeply-inclined beds it not infrequently happens that the dip is greater on one side than the other—the axis is no longer vertical but inclined. And this inequality sometimes increases until the beds on the steeper side of the fold become doubled in below their equivalents on the other side, producing the phenomena of *inversion* (fig. 75, *c*).

A series of such highly-inclined anticlinal and synclinal axes may cause the same beds to crop again and again at the surface ; and when the strata have all the same inclination—forming a series of *isoclinal* folds—it is evident that the apparent thickness of such *isoclinal* strata may be much greater than the actual thickness. In the section (fig. 76) we see the bed L comes to the surface seven times, and did we not know the geological structure of the ground we might suppose that we had seven different beds occurring at so many different horizons in one and the same series of strata. Inversions on a grand scale occur in the Swiss Alps (fig. 77), and inversions of a still more remarkable kind have been recently detected in the north-west of Scotland, but these

Fig. 77.—INVERSION BETWEEN THE SERNTHAL AND THE VORDERRHEINTHAL (HEIM).
c, Cretaceous ; *e*, Eocene ; *f*, Triassic and Jurassic ; *s*, Crystalline schists.

are complicated by dislocations and displacements of a peculiar kind, and will therefore be referred to under the head of *Faults*.

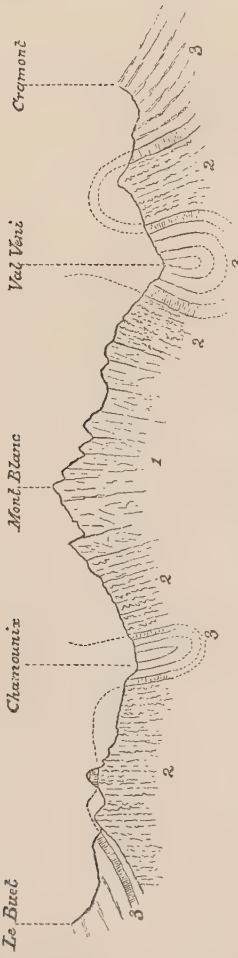


Fig. 78.—SECTION ACROSS MONT BLANC, SHOWING "FAN-SHAPED STRUCTURE." 1, Gneiss; 2, Crystalline schists; 3, Jurassic rocks.

In certain mountain-regions, as in the Alps, we meet with what is termed *fan-shaped structure*. In this structure the rocks appear to be vertical along the axis of the chain, but as they are traversed to right or left they become more and more inclined inwards *towards* the axis. In the section across Mont Blanc (fig. 78) this structure is shown. At 1 the beds of gneiss are vertical, while at 2 2 it will be observed that the crystalline schists dip in apparently under the gneiss, although they are really above it.

5. Outlier and Inlier.—The denudation of strata has given rise to the phenomena known as *outlier* and *inlier*. An *outlier* consists of a patch or mass of rock, surrounded on all sides by strata older than itself; while an *inlier* is just the reverse, and consists of an area of older surrounded by one of younger strata. An outlier, therefore, is a mass of strata detached or separated from strata with which it was formerly continuous, sometimes it may be the sole surviving portion of rocks which at one time covered a wide area. An inlier, on the other hand, is always continuous with strata on its own geological horizon—the beds with which it is continuous being simply concealed under overlying masses (fig. 79).

6. Crumpling and Deformation.—Highly folded and plicated strata (figs. 80, 81), when the folds are irregular and give rise to rapid changes in the angle and direction of dip, are said to

be *contorted*; and the individual beds and layers composing such contorted strata are frequently crumpled and puckered, as if they

Fig. 79.—OUTLIER, O; I I, INLIERS.

had been subjected to great crushing and squeezing (fig. 81). This is likewise suggested by the peculiar deformation which often

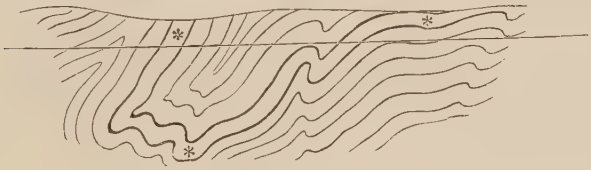


Fig. 80.—CONTORTED ISOCLINAL BEDS. (R.)

characterises the fossils and pebbles that may occur in contorted or highly plicated strata. Stones in conglomerates are often found

Fig. 81.—CONTORTED BEDS: BEDS COMPRESSED AND VERY THIN ALONG LEGS OF FOLDS, BUT THICK AT *a a*.

mutually indented or even compressed and flattened; and fossils have likewise been squeezed out of shape (see figs. 130, 131).

III.—CLEAVAGE.

Although we have not attempted any explanation of the origin of curvature, yet the phenomena described in the foregoing paragraphs must convince us that the force by which strata, thousands of feet in thickness, have been folded and corrugated, must have been intense. Nothing that we see taking place at present produces phenomena at the surface which are at all comparable

to what we may observe in regions of highly disturbed strata. But some of the appearances can be reproduced on a small scale by experiments, and from these we are led to believe that the fissile structure assumed by many fine-grained rocks, such as clay-slate, is, like crumpling and deformation, the result of intense compression. Now this structure, termed *slaty cleavage* from the fact that it is best developed in clay-rocks, must be carefully distinguished from bedding. In true bedding the layers correspond to planes of deposition or accretion, but in slaty-cleavage the planes along which the rock splits may or may not coincide with bedding-planes. In point of fact they rarely do, but intersect the planes of bedding at all angles (fig. 82). Slaty cleavage is therefore a super-

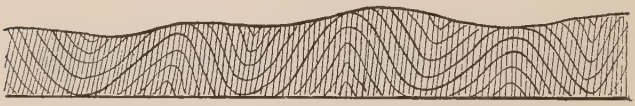


Fig. 82.—CLEAVAGE.
The undulating lines = *bedding*; the straight lines = *cleavage*.

induced structure, the result of compression. It is a kind of deformation on the large scale. When clay-slate is viewed under the microscope the small grains of which it is made up are found to be flattened and compressed in one and the same direction, and this direction corresponds to that of the planes of cleavage. It is, in fact, the compression of its ingredients which has given rise to the cleavage of clay-slate, and it will be readily understood that the cleavage-planes must be arranged at right angles to the direction of the force that produced them. Although slaty cleavage is best developed in homogeneous clay-rocks it occurs in many coarser-grained rocks as well, such as greywacké and even sometimes in conglomerate, but in such coarse-grained masses it is never so perfect as in the finer-grained slates. As a rule cleaved rocks split most readily along the planes of cleavage, the planes of bedding being very frequently welded firmly together. Cleavage is only met with in strata which have been more or less highly folded and plicated, and there can be little doubt that it owes its origin to the same force that folded the strata. This is proved by the fact that the direction of the cleavage-planes is always parallel to the axes of the anticlinal and synclinal folds. [It is possible that the lamination of some clay-rocks may in certain cases be the result of the pressure effected by the mere weight of overlying strata.]

IV.—JOINTS.

The phenomena of deformation and cleavage prove that strata have been subject to great compression; indeed, folding and plication alone are sufficient to demonstrate this. But the movements to which rocks have been subjected frequently induced strain and tension, to which the rocks yielded by cracking across. Division-planes due to this and other causes (such as contraction) are termed *joints*. In fine-grained homogeneous rocks they are usually close and often invisible to the naked eye; while in coarser-grained rocks they are as a rule more strongly marked, and even often gaping. They are met with in every kind of rock, and while frequently very irregular they yet generally tend to group themselves in certain directions. In some sections or exposures of strata we may note that certain beds are traversed by more numerous joints than others; that many of these joints are quite local, while others may cut all the beds in succession. Again, we may observe that, while many of the more local joints run in irregular directions, all the longer joints often seem to have approximately the same trend. In a series of regularly-bedded sandstones and shales, or in such homogeneous rocks as limestone, joints are generally well developed, more or less at right angles to the bedding, so that if the beds be horizontal the leading joints will be vertical or nearly so. Two sets of main or principal joints are usually recognisable (termed *master-joints*), which cut each other at approximately right angles, and thus the strata, by means of bedding-planes and joints, are divided into blocks of a cuboidal form. When the strata are inclined one set of master-joints will be found to run in the direction of the strike and the other in that of the dip, and hence we have what are termed *strike-joints* and *dip-joints*. Such master-joints often maintain their direction with great constancy for long distances, but usually one set (strike-joints) is better developed and more constant than the other. Were it not for the presence of such joints quarrying would be a much more difficult operation, especially in unstratified massive rocks. Although the joints in massive crystalline rocks are rarely so regular as those met with in many fine-grained sedimentary rocks, yet even they not infrequently show considerable regularity, especially when they are traced out on the large scale. And now and again the more or less vertical joints in such rocks that correspond to the master-joints in sedimentary strata are cut across by approximately horizontal division-planes which thus simulate the appearance of bedding. A peculiar kind of jointing is met with in certain crystalline igneous rocks

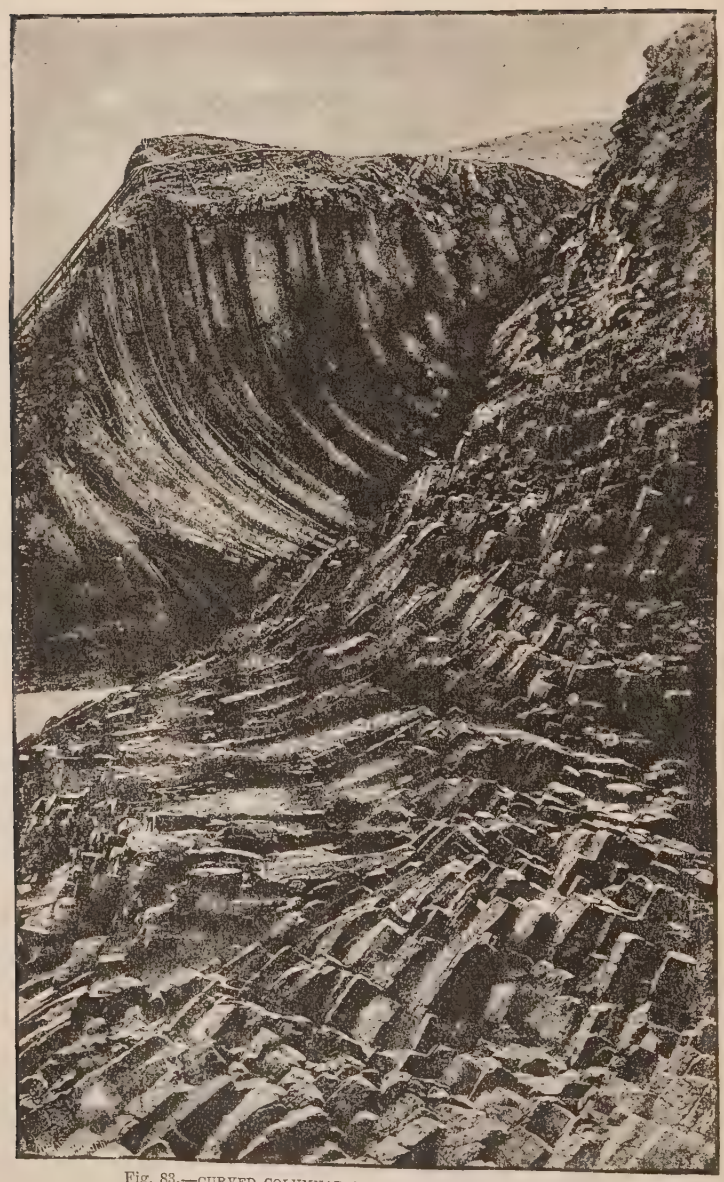


Fig. 83.—CURVED COLUMNAR STRUCTURE IN BASALT: STAFFA.

(more particularly in the finer-grained basalts, although it is by no means confined to these). In the kind of jointing referred to the division-planes meet each other in such a way as to form a series of polygonal (frequently more or less perfect hexagonal) prisms. The basalts of Staffa and Giant's Causeway are familiar examples. Very often the columns are curved in various directions (see fig. 80). These prisms are usually divided by transverse "ball and socket" joints. (For remarks on the influence of joints in denudation, see p. 83.)

The prismatic form assumed by some basalts and other crystalline rocks is believed to be the result of contraction on cooling—the joints are *fissures of retreat*. It is probable that many joints which occur in sedimentary rocks may also have been formed during the gradual consolidation of the strata. But the contraction that took place during the drying and consolidation of rocks will hardly account for the phenomena presented by the strike- and dip-joints, nor for the fact that such division-planes, when they traverse conglomerates, cut across the stones as readily as the matrix in which these are set. It is evident that some considerable force was required for the production of such regular division-planes. Various observations of the famous French experimental geologist Daubrée lead to the conviction that master-joints, at all events, and probably many less regular division-planes, are the result of the stress and strain to which the rocks were subjected when they were disturbed and tilted.

Slickensides.—The faces of joints are often marked with parallel striæ or scratches, as if the opposite walls of rock had been rubbed or ground against each other: these markings are called *slickensides*.

V.—FAULTS.

Rocks have not only been tilted out of their original position, cleaved, and jointed, but they have likewise been fractured, and displaced or shifted along the line of breakage. Strata thus shifted are said to be *faulted*, and the fissure along which the displacement occurs is termed a *fault*, *dislocation*, or *throw*. Faults may occur with or without distortion of the fractured rock-masses. Sometimes the fissure is not more marked than a well-defined joint-plane—it may be close and even. In other cases the rocks are more or less distorted and jumbled along the line of throw, and the fissure is not infrequently filled with a breccia of blocks and débris, forming what is called *fault-rock*, which may vary in width from a foot or two up to several yards. Much depends upon the character of the rocks which are fractured—faults traversing a series of more

or less well-bedded and homogeneous strata tending to be smooth and even; while in rocks of variable structure and petrological character faults are often irregular (fig. 84). In these respects they resemble joints. In well-bedded sandstones and shales, for example, faults usually cut more or less evenly through the beds. But in massive irregularly-jointed crystalline rocks or in a series of strata consisting of rapid alternations of rocks of various degrees of frangibility, the faults are not only uneven but the sides of the fractured strata approach and recede from each other in a very irregular manner. Slickensides are commonly met with in the walls of faults, and in the joints of the rocks adjoining faults. Faults are rarely quite vertical, their inclination from the vertical being termed the *hade*. The following section (fig. 85) shows one of

Fig. 84.—FAULT OF IRREGULAR WIDTH.

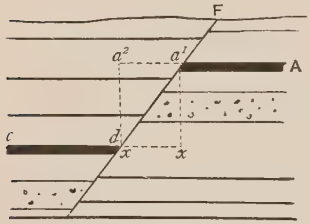


Fig. 85.—FAULT IN HORIZONTAL STRATA.

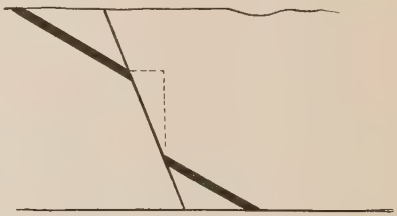


Fig. 86.—FAULT IN INCLINED STRATA.

the simplest forms of fault. Here we have a succession of sandstones, shales, and coal, which have been broken across and shifted along the line F without any distortion of the strata. The degree of vertical displacement of the beds is the *amount* of the throw, and is measured by protracting a line (a^1 . . . a^2) across the fault from the truncated end of some particular bed until a perpendicular (a^2) dropped from the protracted line can reach the other end of the selected stratum. In the case of horizontal strata it is obvious that the amount of vertical displacement or throw is equal to the thickness of the beds displaced (a^2 . . . d). A miner working in the direction from A to a^1 would describe the fault as a *downthrow* or *downcast;* but if he approached the dislocation from the direction *c d* he would term it an *upthrow* or *upcast.* It is evident that the

degree of *lateral* displacement must vary with that of the *hade*, so that an insignificant vertical displacement with a high hade will produce a wider *lateral* separation of the truncated strata than a great fault with a low hade. In fig. 85 the space lying between *x x* we may suppose is 200 feet, but with a less steeply-inclined fault this space would be increased; while with a vertical fault there would be no lateral shift at all. Fig. 86 shows the vertical displacement of inclined strata. It will be observed that the amount of throw in this case is greater than the thickness of the displaced strata. Although faults without distortion of the strata are not uncommon, yet as a rule the fractured ends of the beds appear as if they had been dragged down in the direction of the downthrow and pulled up on the opposite side of the fracture, as in fig. 87.

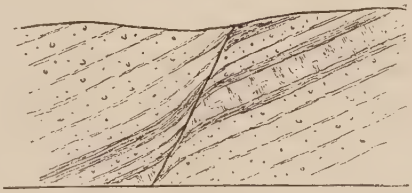


Fig. 87.—FAULT WITH DISTORTION OF STRATA.

Large faults, that is, faults with a great vertical displacement, have generally a low hade; or, to put it in another way, the plane of such faults is usually inclined at a high angle to a horizontal plane. But to this rule there are many exceptions. Some great displacements, to be afterwards referred to, approach the horizontal. Notwithstanding such exceptions it is generally true that faults with great displacement have a low hade, varying, it may be, from vertical up to 40° or more from the vertical. Small faults hade at all angles from vertical up to 70° or 80° from the vertical; in other words, they sometimes approach the horizontal. Usually they are not so steeply inclined from the horizontal as larger ones. Both large and small faults tend to run in approximately straight or gently-undulating lines; but occasionally they form curving lines.

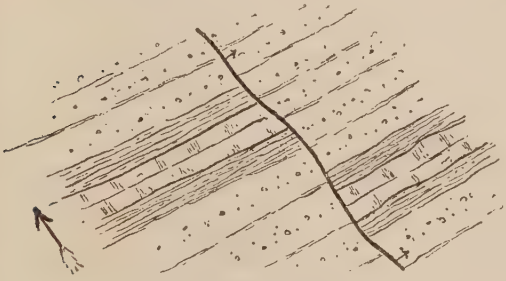


Fig. 88.—GROUND-PLAN OF FAULT.

The effects produced by faults upon outcrops at the surface are

Fig. 89. - APPARENT LATERAL SHIFTING OF OUTCROP BY FAULT.

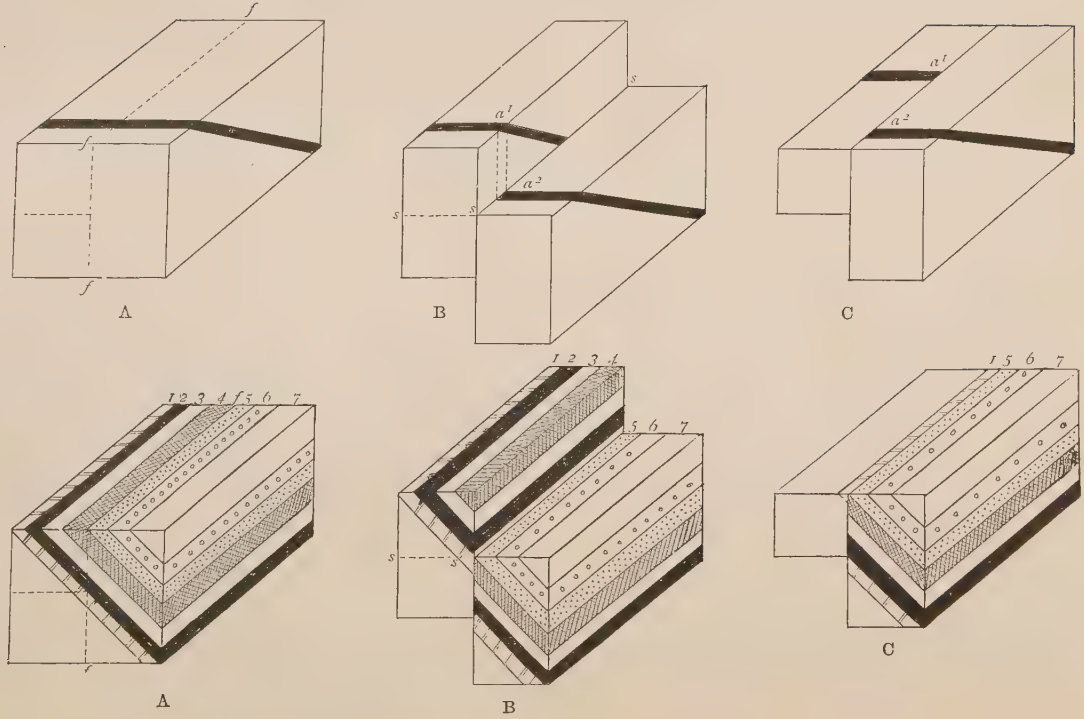


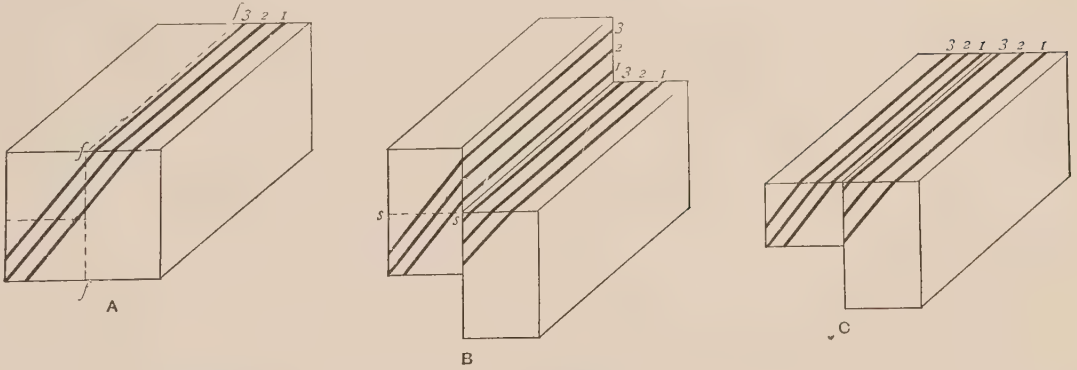
Fig. 90.—EFFECT PRODUCED ON OUTCROPS BY STRIKE FAULT WITH DOWNTHROW IN DIRECTION OF DIP.

sometimes rather puzzling to beginners. The phenomena at first sight are suggestive rather of lateral shifting than vertical displacement. In fig. 88, for example, we have a ground-plan showing the outcrop of certain strata dipping in the direction of the large arrow, and traversed by a fault having its downthrow to the right in the direction of the small arrows. The apparent lateral shift produced by the fault is simply the result of denudation, as a glance at the models (fig. 89) will make plain. Let A represent a block of strata dipping in one determinate direction. A dislocation, we shall suppose, takes place along the interrupted line *f f*. In B we have the same model showing the vertical displacement effected. It will be observed that a line dropped from the truncated end of the bed a^1 to its disconnected continuation a^2 is a perpendicular—the fault is a vertical displacement. Now let us suppose that the surface is cut even by denudation along the line *s s*. The portion above this line we remove, and we have in C a ground-plan of the new surface thus produced. It now becomes evident that the lateral shift is only apparent, and is simply caused by the removal of strata from the upcast side of the fault.

Let us now take the case of a fault that traverses strata along the line of strike. In fig. 90, A, we have a model of strata which we shall suppose are dislocated along the line *f f*. B shows the same model with the vertical displacement effected, the fault being in this case a *downthrow in the direction of the dip*. Now let us, as before, remove the higher portion of the model, above the line *s s* in B, and we have the ground-plan as shown in C. The effect of such a strike-fault in the direction of the dip is to cut out strata—to carry their outcrops below the surface. In the area represented by the model A, we have a considerable thickness of strata, consisting of beds marked 1, 2, 3, 4, 5, 6, 7. The same beds are shown in C; but it will be observed that some of these no longer crop out at the surface, but under the surface and against the dislocation. The beds 2, 3, and 4 are cut out, as it were.

The next group of models (fig. 91) shows the effect produced at the surface by a *strike-fault with its downthrow against or in the opposite direction to the dip* of the strata. The result of such a fault is precisely the opposite of the one just described. Instead of cutting out strata at the crop or surface, it causes the outcrops to be repeated. A glance at the models (fig. 91) will explain how that happens. In A we have the strata as they appear before displacement is effected along the line *f f*. B shows the dislocated strata; and in C we have the effect produced at the surface by the removal of the block projecting above the line *s s*—the truncated ends of the beds (1, 2, 3), being brought up and caused to re-crop as it

Fig. 91.—EFFECT PRODUCED ON OUTCROPS BY STRIKE-FAULT WITH DOWNTHROW AGAINST THE DIP.



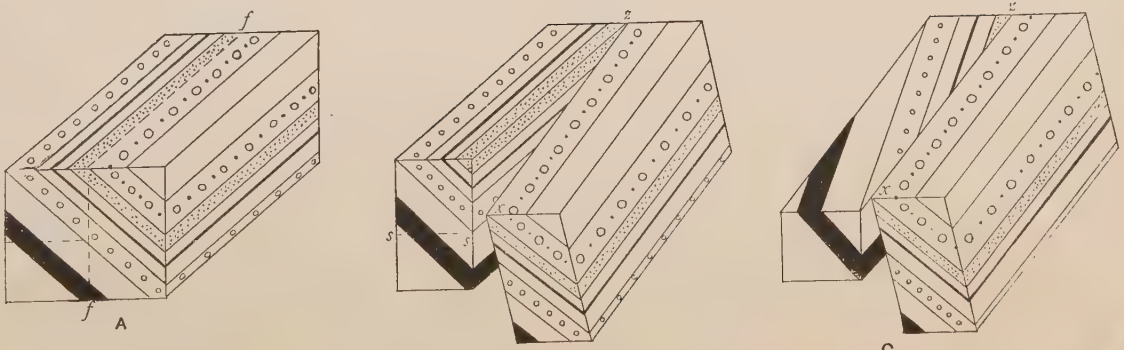


Fig. 92.—EFFECT PRODUCED ON OUTCROPS BY STRIKE-FAULT WITH A DIMINISHING DOWNTHROW.

were, so as to present the deceptive appearance of six beds all dipping in the same direction.

Strike-faults are apt to be overlooked when they coincide more or less closely with the line of bedding. Thus an observer traversing either of the areas shown in the models (figs. 90, 91), might easily fail to detect any evidence of dislocation, and might be led to suppose that he had before him continuous successions of strata ; and thus in the one case he might assign too small and in the other too great a thickness to the series. But it is only under rare circumstances that a fault keeps continuously to the strike, more usually it undulates from one side to the other ; and as the dip of the strata changes, while the fault continues in approximately the same direction, the observer can hardly fail to detect it by the more or less abrupt truncation of the strata which it produces the moment it leaves the strike and begins to traverse the strata. But even when it keeps to the strike it often betrays its presence by variations in the amount of its downthrow. Every fault, if it only be followed far enough, will be found to diminish in extent until eventually it dies out altogether. We may suppose it to begin at zero, gradually to acquire its maximum of downthrow, and then to diminish until zero is reached at its farther extremity. In other words the strata are cracked along a certain line, and sink down on one side of that line, the depression being greatest as a rule at a point about midway between the two ends of the crack. The effect of such a strike-fault with diminishing downthrow is illustrated in the models (fig. 92). As in preceding illustrations A represents the strata before displacement along the line *f f* has been effected. In B the fault has taken place, the amount of downthrow being at a maximum at *x* but gradually diminishing towards *z*, where it dies out. When the portion projecting above *s s* is removed we have the appearance shown in C, which represents the new surface produced by denudation. It will be observed that upon the upcast side of the fault lower beds successively appear as the fault is traced from *z* to *x*.

The apparent lateral shifting of the outcrop is well exemplified in the case of faults that traverse anticlinal and synclinal folds. Let A (fig. 93) represent a block of strata arranged in the form of a syncline which is eventually fractured and displaced along the line *f f*, as is shown in B. Now when denudation has removed the strata on the high side of the fault and reduced the whole area to approximately the same level (*s s*), the outcrops will represent the appearance shown in C. From this it is evident that the result of a fault crossing a syncline is to produce an apparent contraction of the outcrops on the upcast side, and an apparent widening of the

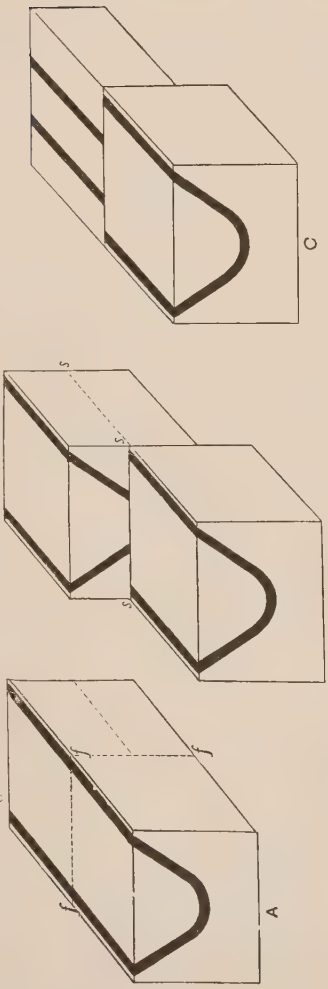


Fig. 93.- EFFECT PRODUCED ON OUTCROPS BY FAULT TRAVERSING SYNCLINAL STRATA.

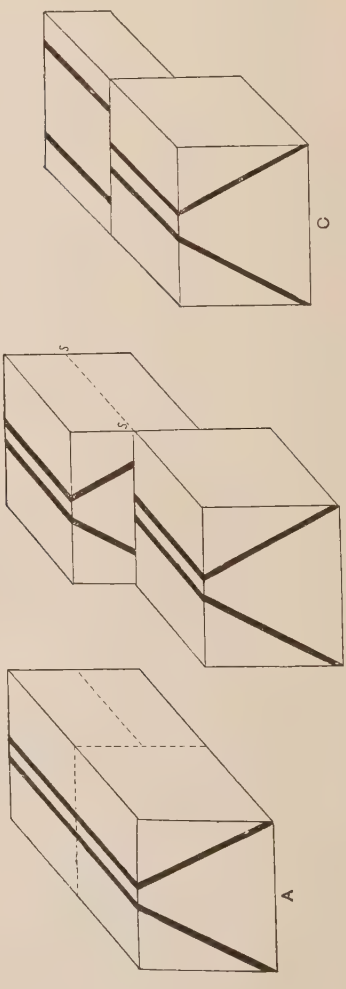


Fig. 94.—EFFECT PRODUCED ON OUTCROPS BY FAULT TRAVERSING ANTICLINAL STRATA.

corresponding outcrops on the downthrow side of the fault. Similar phenomena occur when a fault cuts across an anticlinal arch, as may be seen by examining fig. 94. The arch before dislocation is represented by A, while B shows the appearance after dislocation has taken place. When we remove the portion lying above the dotted line (*s s*) we have the new surface (C) produced by denudation, upon which the crops on the upcast side appear to have been shifted laterally, but in the opposite direction to the apparent shifting produced by a fault traversing synclinal strata. Thus in the case of a faulted anticline the opposing outcrops on the higher side of the dislocation appear to widen out, while on the low side the same outcrops seem to have been brought closer together, the apparent lateral shifting being of course entirely the result of denudation.

We have been describing faults as if they were always single, and more or less isolated. But faults of any importance rarely occur alone. Large faults are usually accompanied by lateral dislocations with downthrows in the same or opposite directions (fig. 95). So numerous and close indeed are such parallel dislocations in some cases that it is often impossible to say which is the main fault.

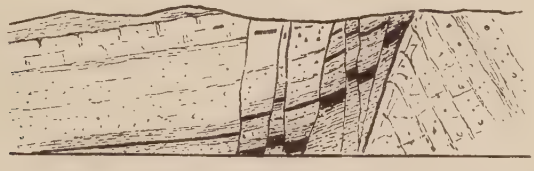


Fig. 95.—COMPOUND FAULT.

Again we may have a series of more or less parallel faults separated from each other by a greater or less width of undisturbed strata. The downthrows may all be in one direction (figs. 97, 98),

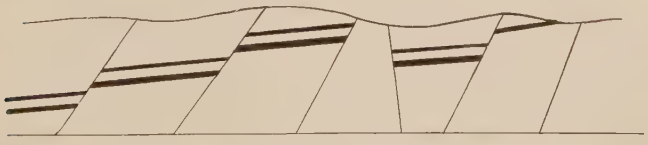


Fig. 96.—STEP FAULTS.

or some may be in one direction and some in another (fig. 96). The result of such faults is to produce a step-like arrangement of the strata, hence the term *step-faults*. Such parallel faults when they run in the direction of the strike, and have their *downthrow with the dip of the strata*, simply repeat the phenomena which are

shown in fig. 90 ; they tend to prevent certain outcrops from appearing at the surface ; while a succession of step-faults with *down-*

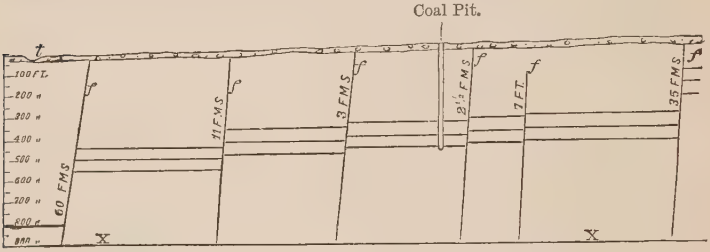


Fig. 97.—STEP-FAULTS IN COAL-MEASURES (NEAR WISHAW).
(Horizontal and vertical scale the same.)

throws against the dip of the strata cause the same beds to crop again and again as in the following diagram (fig. 98), which should be compared with the models in fig. 91 :—

Fig. 98.—STEP FAULTS : DOWNTHROW AGAINST DIP.

When parallel or approximately parallel faults have downthrows in different directions they produce the phenomena of *trough-faults*, as is shown in the accompanying section (fig. 99).

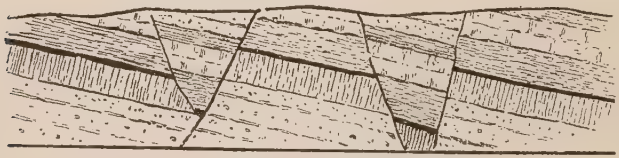


Fig. 99.—TROUGH FAULTS.

When the faults of a district have been traced out it is often found that these arrange themselves into two more or less well-marked groups—one of which may run approximately in the direction of the prevalent strike of the strata, and the other may tend in the direction of the dip. Hence such groups are often spoken of as *strike-faults* and *dip-faults*. In many cases dip-faults

seem to be the more numerous, but strike-faults are apt to be the more important. In fact, it would not infrequently appear as if the movements that produced strike-faults had also given rise to the dip of the strata along the line of such faults. This is particularly the case with the great faults that often form the boundaries between formations, as, for example, the great strike-faults that separate the Old Red Sandstone and later formations from the rocks of the Highlands and Southern Uplands of Scotland.

Faults having the same trend, but with their downthrows in different directions, often coalesce, and either suddenly terminate at the point of union, or one dies out and the other continues with usually a diminished amount of downthrow. But when approximately-parallel faults, having their downthrow in one direction, coalesce, they almost invariably continue as a single fault with an increased amount of downthrow.

Although groups of faults have been described as strike-faults and dip-faults, it must not be supposed that it is always possible thus to classify the faults of any particular area. Not infrequently they seem to form a kind of irregular network, meeting and intersecting each other at all angles. Observation has shown that while the faults occurring in some particular district may belong approximately to the same age, yet very often this is not the case. Not infrequently we have one set of faults crossed and shifted by a later set, the older faults showing at the surface an apparent lateral displacement, just in the same way as faulted strata.

The amount of vertical displacement produced by faults may vary from an inch or two up to many thousand feet. The great fault between the Highlands and Lowlands just referred to, has a downthrow in Perthshire of some 8000 feet; while that of the similar fault between the Lowlands and Southern Uplands reaches in places fully 15,000 feet.

Fig. 100.—FAULT WITH IRREGULAR HADE.

The phenomena described in the foregoing paragraphs have reference to what we may call normal faults which invariably hade in the direction of downthrow. Occasionally, it is true, we may have a normal fault which seems to hade in the opposite direction; but this may be a mere irregularity in the form of the fissure, as in the accompanying diagram. At *a*, *b*, *c* (fig. 100), the fault is seen to hade in the direction of the downthrow, while at *d* and *e* the hade is not with but against the direction of downthrow.

There is a certain class of faults, however, in which the hade is distinctly not in the direction of the downthrow—these are called *reversed faults* (fig. 101). They rarely occur in strata which

Fig. 101.—REVERSED FAULT.

are not highly folded and plicated, but amongst such strata they are by no means uncommon. Unfortunately it is rather difficult to estimate thicknesses in such contorted strata, and consequently to form any adequate conception of the amount of displacement effected by reversed faults. But this seems to vary very much just as in the case of normal faults. Normal faults with a great downthrow tend, as we have seen, to incline more steeply from the horizontal than those whose downthrow is inconsiderable. The contrary would seem to be the case with reversed faults, those having the steepest inclination from the horizontal showing usually less displacement than reversed faults whose inclination approaches the horizontal. Recently some extraordinary reversed faults have been described by Messrs. Peach and Horne as occurring in the north-west of Sutherland. The inclination of these faults from the horizontal is so gentle that they might sometimes be described as approximately horizontal, so that the strata on the high side overlie the rocks on the lower side of the fault, like successive strata in a conformable series. One set of rocks belonging to a low horizon has been pushed forward horizontally over the surface of another set pertaining to a higher horizon, so that we have a series of younger rocks covered apparently conformably by a series of very much older rocks. In some places the horizontal displacement produced by those remarkable reversed faults (or *thrust-planes*, as Messrs. Peach and Horne term them), is truly astonishing. At Durness, for example, certain strata have been pushed forward bodily over younger rocks for a distance of not less than 10 miles.

VI.—UNCONFORMITY AND OVERLAP.

When strata occur in regular sequence—each successive bed resting regularly upon the surface of another—they are said to be *conformable*. But when this regular sequence is interrupted, and

one set of beds extends over the denuded surface of another series, we have what is called an *unconformity* or *unconformability*. In the following section (fig. 102), we have a discordant junction

Fig. 102.—UNCONFORMITY AND OVERLAP. (R.)

between two sets of strata, the upper series (2) resting *unconformably* on the upturned and denuded edges of the lower series (1). Such an unconformity necessarily implies a break in the sequence, and the lapse of a long period of time. The lower series (1) must first have been deposited, and subsequently folded, and subjected to enormous denudation which removed the tops of the anticlines so as to expose the truncated ends of the beds. Probably the denudation was in great part subaërial—the rocks may have formed part of a land-surface during some protracted period. But eventually they were submerged—the land-surface sinking gradually, so that newer deposits were laid down over a constantly widening area. A reference to the diagram will show that the upper beds of the series (2) extend beyond the bottom beds of the same series. This is what is termed an *overlap*. Such overlaps must necessarily occur whenever a coast-line is undergoing depression, so that an overlap always implies unconformity, and probably no unconformity can take place without overlap, although we may rarely see the two phenomena in one and the same section. Occasionally two or even three unconformities may occur in one limited area. In fig. 103 a double unconformity is shown.

Fig. 103.—DOUBLE UNCONFORMITY.

As a rule unconformities are not hard to detect, there being usually a marked discordance in the stratification of the rocks. Now and again, however, the two series dip in the same direction, and approximately at the same angle, and often present in single sections the appearance of complete conformability. When, however, they are traced carefully over any considerable area, their actual

discordance will usually be shown by the manner in which the upper slowly steals across the outcrop of the lower series. Unconformable junctions are often marked by the appearance of a conglomerate or pebbly grit and sandstone which forms the lowest bed of the upper series, and is usually largely made up of rounded fragments derived from the denudation of the lower series.

A well-marked unconformity, therefore, generally indicates the following succession of physical changes :—(1) a movement of elevation, followed by (2) terrestrial conditions and more or less excessive denudation ; and thereafter (3) a movement of subsidence and deposition of sediment over a gradually increasing area.

CHAPTER XVI.

ORE DEPOSITS.

Ores diffused or disseminated through rocks—Bedded ores—Ores occurring in fissures, etc.—Ores as constituents of rocks—Metals occurring in rock-forming minerals—Varieties of bedded ores—Placers—Lodes—Gash-veins, pipe-veins, chambers, and pockets—Flats—Impregnations—Stockworks—Theories of the origin of ore deposits.

THE ores of metals occur in various ways, so that they are somewhat difficult to classify geologically, but they may be grouped under these heads :—

1. Ores diffused through the mass of a rock, either as primary or secondary constituents.

2. Ores occurring as sedimentary or chemical deposits, and forming beds in a group of strata.

3. Ores occupying cracks, fissures, and irregular cavities in rocks.

I.—DIFFUSED ORES.

Frequent reference has already been made to various ores (such as magnetite, ilmenite, etc.) which occur both as primary and secondary constituents of many crystalline rocks. Minute quantities of iron and of many other metals (such as gold, silver, copper, cobalt, nickel, arsenic, bismuth, lead, etc.) have been detected in the mineral constituents of various crystalline rocks, so that those metals are probably much more widely distributed than was at one time supposed. It is true that the proportion of metallic substance present in any individual crystal of augite, mica, orthoclase, olivine, or other mineral is very minute, but the total amount thus contained by many crystalline rocks must be very considerable. Occasionally ores are met with disseminated through sedimentary strata in such a way as to suggest that they have been deposited by the chemical action of percolating water. Sometimes they occur as small, often microscopic, crystals or rounded grains and concre-

tions, or as pellicles coating the granules and pebbles in the rock; at other times they seem to replace organic remains—stalks, leaves, and fruits having been converted into some metallic ore—or they may occur as strings traversing the fossils, or as encrustations upon their external surfaces. Examples of these phenomena are common in the copper-bearing beds at Mannsfeld and Frankenberg in Germany. The well-known deposits of native copper in the Lake Superior region may be included in this group. It lines and fills vesicles in certain igneous rocks, occurs also in joints and clefts, and is diffused through the matrix of breccias and conglomerates. It is met with also in true fissure-veins in the same region.

II.—BEDDED ORES.

Ores occurring as bedded, sedimentary, or chemical deposits in a group of strata need not be described here, as their general characters have already been given. Among the more typical ores of this kind are the various forms of argillaceous carbonate of iron, such as *clay-ironstone*, *blackband-ironstone*, etc. Iron ores, such as *hæmatite* and *magnetite*, sometimes form massive beds associated with a class of rocks which we have not yet described—the *Crystalline Schists*. The largest masses of magnetite in Europe occur at Gellivara in Swedish Lapland, where one of the beds reaches nearly 200 feet in thickness, and extends over a wide area. It is, however, contaminated with various impurities, but a thickness of about 120 feet is suitable for iron-making.

Some of the clay-ironstones included under the group of bedded ores are evidently the result of segregation. Originally the mineral matter was probably disseminated through the shales in which the ironstone nodules occur, so that no hard and fast line can be drawn between the ores of groups 1 and 2.

Under the same group are included alluvial deposits which contain the water-worn débris of metallic ores. Such ore-bearing deposits are termed *placers*. The metals obtained from placers are principally gold, platinum, and cassiterite (stream-tin). The principal deposits are the auriferous gravels of California and New South Wales, and the auriferous and platinum-bearing gravels of the Urals in Russia. The tin-bearing gravels of Cornwall have long been famous, but are now practically exhausted. Placers appear to be of no great geological antiquity—none apparently dating back beyond the Tertiary period.

III.—LODES, ETC.

The third group of ore deposits embraces a variety of accumulations which are known to miners under many different names, such as *lodes* or *veins*, *stockworks*, *pockets*, etc.

Lodes.—When the fractures, fissures, and dislocations which traverse rocks are filled or partially filled with ores and other minerals, they form what are termed *lodes*. Most of the larger lodes occur in true faults. They are generally steeply inclined, sometimes vertical, but occasionally their inclination is moderate. They vary much in thickness—from less than an inch up to several hundred feet. And there is often great variation in the width of one and the same lode. The non-metallic contents of a lode, called *vein-stuff*, consist largely of crystallised minerals, such as quartz, fluor-spar, calcite, and barytes; but often these are mixed up with blocks and débris of the adjoining rocks, or with clay, etc. The ores themselves sometimes occupy the whole width of the lode; at other times they occur as irregular veins, strings, layers, nodules, or grains in the vein-stuff. Many lodes are composed of more or less regular alternations of crystalline minerals and ore, arranged in parallel and corresponding sheets on opposite sides of the fissure, as is shown in fig. 104, where the walls of the vein are lined with quartz-crystals, the apices of which point inwards. Succeeding the quartz-layers come two corresponding sheets of galena (sulphide of lead), and these are followed by deposits of siderite (carbonate of iron). A regular lode of this kind is called a *comby lode*. Very often veins after having been filled up with mineral matter have again been opened, and the cavity thus produced has in like manner become filled with new depositions of mineral matter, as is shown in the annexed section (fig. 105). In this case we may suppose that *a b*

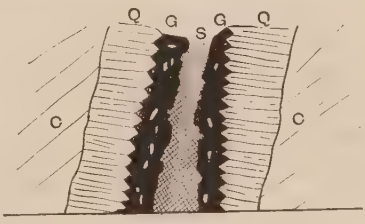


Fig. 104.—COMBY LODE.
Q, Quartz; G, galena; S, siderite; C, "country."

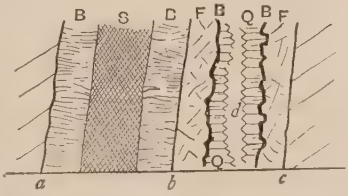


Fig. 105.—RE-OPENING AND RE-FILLING OF LODE.
a b, Walls of original fissure, filled up with B (barytes) and S (siderite); *b c*, walls of re-opened fissure lined with F (fluor-spar), B (blende), and Q (quartz); *d*, druse.

represent the walls of the original fissure, which were lined with sheets of barytes (B B), and the intervening vacuity at length completely filled with siderite (S). The fissure being reopened, *b* and *c* then became the walls, and successive deposits of fluor-spar (F), blende (B), and quartz (Q) were formed, leaving a vacuity in the centre called a *druse* (*d*). Reopening of veins has often been accompanied by shattering of vein-stuff and the adjoining walls of the fissure, and this has given rise in many cases to what are termed *brecciated lodes*. In these brecciated lodes slickensides are often present. In other cases the breccia consists of fragments which have been derived from the adjoining walls of the fissure at the time the original rent in the rocks took place—the rock-fragments having been subsequently cemented together by infiltrations of ore or other mineral matter.

The rock which encloses or is traversed by a lode is called the *country*, and the *walls* or *cheeks* of a vein are of course those portions of the country with which it is in contact. In the case of inclined veins that wall which is above the lode is called the *hanging-wall*, while that on which it seems to rest is termed its *foot-wall*. The inclination of a lode from the vertical is called its *hade*, and the line along which the vein comes to the surface is its *outcrop*, *outgoing*, or *back*,—*gossan* being the name given to the weathered back of a lode. The band of altered rock or other material, which often comes between the vein and its country, is termed *selvage*, *flucan*, or *salband*.

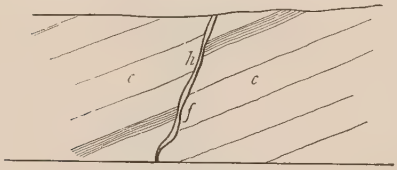


Fig. 106.—SECTION OF LODE.
c, Country; *h*, hanging-wall; *f*, foot-wall.

In their direction and grouping lodes follow the same rules as faults, in which, as we have seen, most lodes occur. Not only do they vary in width, but they vary much in longitudinal extent. Like faults and strata they are also liable to be intersected by other veins, and shifted or *heaved* so as to show apparent lateral displacement at their outcrops.

Gash-veins, Pipe-veins, Chambers and Pockets, Flats.—Besides the regular lodes or "true veins" described above there are many ore deposits which occur in irregular clefts and cavities in rocks, and have acquired different names from miners, although their origin is probably the same as that of the ores that occur in "true veins." The cavities so commonly met with in limestone rocks are not infrequently charged with metalliferous deposits, such as galena, blende, iron pyrites, hæmatite, etc. *Gash-veins* (fig. 107) are deposits of ore occurring at the point of intersec-

tion of division-planes in limestone, where gash-like cavities have been formed by the action of acidulated water. *Pipe-veins* again occupy approximately vertical and rudely cylindrical pipes in limestone; while *chambers* or *pockets* is the name given to larger or

Fig. 107.—*g*, Gash-veins; *f*, flats; *p*, pipe; C, chamber.

smaller ore deposits filling up irregular cavities in calcareous rocks. *Flats* are accumulations of ore along the line of bedding. They may occur in connection with gash-veins, etc., or with true veins, when they seem to spread out from the lode laterally.

Impregnations.—Not infrequently the rocks forming the country traversed by a lode are impregnated to a greater or less degree with mineral matter, which may occur in the form of minute crystals or crystalline particles or spherical aggregations. And now and again such impregnations are sufficiently rich to be worked. Occasionally they have no connection with any vein or lode, and in such cases they would come under our first group.

Stockworks.—When a rock-mass is intersected by numerous veins, branching and interlacing to such an extent that it can be mined in successive *floors*, it is called a *stockwork*. The ores are not necessarily confined to the veins, the rock being often impregnated with them.

Thus we must conclude that no strong line of demarcation separates the various kinds of ore deposits mentioned above. We may say, however, that all metals and ores of metals are either (1) original constituents of rocks, or (2) results of the chemical rearrangement of the mineral elements of rocks, or (3) subsequent introductions of mineral matter diffused through the body of rocks or accumulated in fissures, vesicles, and irregular cavities.

The observations of Professor Sandberger and others have led to the growing belief that the ores which are mentioned here as "subsequent introductions" have been derived by the action of percolating water from metalliferous rocks. We know now that many minerals

contain minute quantities of metals. Thus Sandberger has found that iron, copper, cobalt, nickel, lead, tin, and zinc, and sometimes also antimony and arsenic, are often present in augite. In olivine, iron, copper, nickel, and cobalt are constantly met with. The micas have been found by the same observer to contain such metals as tin, arsenic, copper, bismuth, uranium, lead, zinc, cobalt, and nickel. It seems, therefore, highly probable that not only the vein-stones (quartz, calcite, fluor-spar, etc.), but also the ores which occur in lodes, etc., have been derived from the surrounding *country* and carried in a state of chemical solution into the places where we now find them. This explains the often observed fact that the richness of lodes seems frequently dependent on the nature of the rocks which they traverse. Thus in Derbyshire the lodes which traverse limestone and certain interstratified igneous rocks generally contain lead-ore when limestone forms the *country*, but the ore is usually absent while the lode passes through the associated igneous rocks. Again, at Kongsberg in Norway, there are certain bands of rock called *fahlbands*, which are impregnated with the sulphides of various metals. These fahlbands are intersected by veins which are metalliferous at such points but nowhere else—a fact which seems to suggest that the veins derived their ores by chemical agencies from the fahlbands. In many cases, however, it is impossible to trace any connection between the contents of lodes and the nature of the country rock. It is conceivable, however, that mineral matter carried in solution into a vertical or inclined fissure might often travel long distances before it came to be deposited on the walls. Some writers think it probable that lodes have been largely filled by mineral matter brought up from below in a state of solution. At great depths water, owing to increased heat and pressure, will have its solvent power intensified, and thus solutions of mineral matter will take place there more readily and be carried upwards and deposited at higher levels. It has likewise been suggested that at great depths the pressure of the superincumbent column of water may sometimes force solutions into the surrounding rocks and thus bring about the phenomena of *impregnations*. Various other hypotheses have been advanced in explanation of the origin of metalliferous veins, such as that of *electric currents*, which sought to account for the deposition of ores in veins by the action of galvanic currents in metallic solutions; but it leaves us in the dark as to the origin of the metallic solutions. Another hypothesis is that of sublimation from below of volatilised metals and metalliferous minerals derived from the highly heated regions underneath the earth's crust. This view, however, leaves much unexplained. It is possible, however, that sublimation, accompanied perhaps with

steam, may sometimes have assisted in the formation of lodes. It would seem, therefore, that the theory of *ascension of heated solutions*, combined with that of the *lateral secretion of mineral matter from adjacent rocks*, gives us the best explanation of the phenomena of vein deposits as a whole.

In most lodes layers of clay or earth are met with which in many cases are the results of the action of percolating water upon the country rock, which is often more or less decomposed for some considerable distance away from the cheeks of the vein. But sometimes the clay seems to have resulted from the grinding together of the walls of the fissure, and to consist, therefore, of pulverised rock. It is frequently slickensided and marked with long parallel furrows and lines.

CHAPTER XVII.

ERUPTIVE ROCKS: THEIR MODE OF OCCURRENCE.

Volcanic and plutonic rocks—Contemporaneous eruptive rocks—General phenomena of lava-flows and bedded tuffs, etc.—Fissure eruptions; general character of their products—Intrusive eruptive rocks—Necks—Intrusive sheets—Dykes and veins—Bosses; their segregation- or contemporaneous-veins.

Having reviewed the more important phenomena connected with the original and superinduced structures of rocks we pass now to consider the appearance presented by rock-masses in the field. Enough has already been said under the head of stratification, etc., to give the student a fair notion of the mode of occurrence of stratified sedimentary rocks, and we shall return to the subject in a later chapter when we come to discuss the origin of those rock-structures (folding, cleavage, faults, etc.) which have been described in preceding pages. For the present, then, we confine attention to the phenomena of eruptive rocks.

The petrological examination of those rocks led us to conclude that many are strictly analogous to modern lava-flows and ejections of fragmental matter. But others, as we saw, must have consolidated at considerable depths under great pressure, and never could have flowed out as lavas at the surface. Geologists, therefore, recognise two kinds of eruptive rocks, namely, *volcanic rocks*, consisting of lavas and tuffs, etc., which have been ejected at the surface, either upon the land or under water, and *plutonic rocks*, which, whether consisting of crystalline or fragmental materials, have not been so extruded, but are now exposed owing to the denudation of rock-masses underneath which they were formerly concealed. It is thus usual to speak of volcanic rocks as *contemporaneous*, by which we mean that they belong to the same age as the strata with which they are *interbedded*, while plutonic rocks are described as *intrusive* or *subsequent* because they have been *intruded* amongst, and are therefore *subsequent* in date to the rocks with which they are immediately associated.

I.—CONTEMPORANEOUS ERUPTIVE ROCKS.

These present us with many of the most striking volcanic phenomena. They consist either of *crystalline* or *fragmental materials.*

Crystalline.—The crystalline rocks are lava-flows, and like these vary much in thickness and lateral extension. As a rule, they are most markedly crystalline towards the centre, and usually become finer-grained towards top and bottom, where likewise they frequently assume a vesicular structure, the vesicles being often filled up with mineral matter. Generally speaking, they seem to have had little effect in "baking" and otherwise altering the underlying rocks. Now and again the pavement upon which they rest may be more or less hardened and irregularly cracked as if from the influence of heat, but such contact-effects are rarely traceable more than a few inches downwards. Occasionally, however, portions of the underlying bed of sandstone, shale, or other rock, are caught up and

Fig. 108.—SECTION OF CONTEMPORANEOUS LAVA-FLOW

included in the volcanic rock. Very often it would seem that this had taken place when the sandstones, etc., were as yet unconsolidated—as if the lava had flowed over the floor of lake, estuary, or sea, and involved in its lower portions some of the sedimentary materials gathering there. Sometimes the bottom parts of such old lava-flows contain so much baked sandstone and mud (shale or mudstone) as to resemble rude breccias of volcanic and sedimentary materials. The upper part of contemporaneous sheets of crystalline igneous rock are frequently vesicular, and often highly slaggy and scoriaceous. And now and again some lava-flows are more or less vesicular throughout, the vesicles in most cases being flattened and drawn out in the line of flow. The sedimentary beds resting upon old lava-flows accommodate themselves to all inequalities of surface, and are quite unaltered at their junction with that surface. They have evidently been gradually accumulated, filling up holes and irregular cavities in the lava-flow, and not infrequently con-

tain in their bottom layers fragments of the scoriaceous or vesicular rock, which are occasionally more or less waterworn. Many old lava-flows, indeed, have been much eroded and denuded before their final entombment in sand and mud, the beds resting upon them consisting occasionally of a conglomerate or conglomeratic sandstone largely composed of water-worn fragments of volcanic rock. Many flows exhibit columnar structure, the columns being arranged at right angles to the planes of cooling. When the lava has cooled upon an irregular surface the columns are usually curved.

Although single flows are occasionally met with they more usually occur in groups ; and in both cases they are generally but not always accompanied by beds of volcanic fragmental materials (tuffs). The successive flows in a series of volcanic rocks generally consist of the same kind of rock, although the several beds may vary very much in texture and structure. When flows of different petrological character occur in one and the same series, it seems to be a general rule that the more acidic kind occur towards the bottom and the more basic species towards the top of the series.

Flows of basic rock (such as basalt) often preserve a very equable thickness for long distances ; while individual flows of an acidic rock (such as rhyolite and trachyte) are generally more lumpy and irregular, and seldom cover wide areas. Flows may be of any thickness—some basalts are not more than 10 or 12 feet, while others may exceed 100 feet. Many of the hill-ranges of Central Scotland, such as the Sidlaws and Ochils, the volcanic hills of Ayrshire, etc., are built up of successive flows of andesitic lavas and basalts which have flowed from vents in the manner of modern volcanic eruptions (see fig. 113). The slopes of those hills often present a characteristic terraced appearance, which is caused by the outcrops of the old lavas and their associated tuffs. Some of these eruptions were evidently sub-aqueous, while others appear to have been sub-aërial.

Fragmental.—The tuffs interstratified with flows which have proceeded from vents in the usual way vary much as regards texture and structure. Sometimes they are very fine-grained and well-bedded ; at other times they are coarse, and show little or no trace of bedded arrangement. Some are deposits which have been laid down in quiet water, others resemble tumultuous torrential accumulations, such as might have been swept down the slopes of the old volcanoes by torrents of water, yet others show no trace of water-action—none of the lapilli being water-worn, but forming confused masses in which not infrequently a kind of bedding occurs, like that which one sees in taluses of débris. Now and

again large ejected blocks make their appearance, both in fine-grained and coarse tuffs, and these often increase in size and numbers as the centres of old volcanic action are approached. These blocks are usually fragments of volcanic rocks having the same character as some of the flows of the district in which they occur, or they may consist of sandstone, limestone, or other aqueous rock known to crop out in the neighbourhood. But now and again the blocks belong to rock-masses which have not yet been exposed by denudation. For example, blocks and fragments of granite and certain other crystalline rocks occur in the tuffs of the volcanic hills of North Ayrshire. No doubt masses of these rocks exist underneath the old volcanic area in question, although they nowhere appear *in situ* at the surface.

The petrological character of tuff varies with that of the lavas with which it is associated. Thus we have trachytic tuffs interstratified with trachyte, andesitic tuffs with andesitic lavas, and so forth. In the finer-grained tuffs which often pass laterally into ordinary sedimentary rocks like sandstone and shale, fossils sometimes occur, and these are always valuable as enabling us to fix the geological horizon of the eruptions and the geographical conditions that obtained at the time. Careful examination of the tuffs of an old volcanic region may indeed often enable us to tell whether the eruptions were sub-aqueous or sub-aërial, or whether they were partly one and partly the other.

Although tuffs are generally present in a group of volcanic rocks, yet in many cases they play a very subordinate part, that is to say, the individual beds of tuff are of inconsiderable thickness. The thickest sheets of tuff occur as a rule either alone or in association with single lava-flows.

Fissure Eruptions.—Hitherto we have been describing flows and tuffs ejected from vents of the ordinary type. In some places, however, there occur successions of lava-flows, covering immense areas, which do not appear to have been erupted from isolated vents. These lavas form plateaux, and are well developed in the Western Territories of North America, in Iceland and the Faeröes, in the Deccan, and in Abyssinia; and in many of the Western Islands of Scotland we meet with fragments of similar plateaux. The flows composing those plateaux consist of basalts, which are believed to have welled-up along the line of great fissures, and to have poured in wide floods over the surface, so as eventually to obliterate all the features of the regions in which they occur, and to form vast plains or table-lands. The phenomena presented by such formations are well seen in the Faeröe Islands, where the volcanic series is not less than 13,000 or 14,000 feet in thickness. There we see basalts vary-

ing in thickness from 20 or 30 feet up to 100 feet, each bed running continuously and preserving its thickness for many miles. The basalts are usually separated by intervening layers of fine-grained tuff, varying in thickness from an inch or so up to 100 feet—but tuffs of this thickness are not common. Some of these tuffs are bedded, and along one or two horizons they contain plant-remains and impure coal. All the tuffs are fine-grained, and consist largely of a dull compact red rock, which when viewed in thin slices under the microscope, is found to consist of minute fragments of brownish-yellow volcanic glass and granules and fragments of various volcanic minerals, such as augite and olivine. No trace of beds of lapilli and no ejected blocks occur anywhere in the islands.

II.—INTRUSIVE ERUPTIVE ROCKS.

The intrusive or subsequent eruptive rocks are also met with under two forms—*crystalline* and *fragmental*, and in hand-specimens it is very often impossible to distinguish between intrusive and contemporaneous rocks. The volcanic fragmental rocks which occur in vertical pipes and fissures are not to be distinguished petrologically from some kinds of interbedded tuff—nor are the petrological characters of intrusive crystalline rocks always or even often so well-marked that we can pronounce upon their origin by a mere examination of museum specimens. It is only by studying their relations in the field that we can have any certainty in the matter. There is a certain class of intrusive rocks, however, which have most marked characters. Such are the granites, syenites, and other granitoid masses which have consolidated under great pressure. These, as a rule, cannot be mistaken, even in small fragments, for rocks of the volcanic class. We find nothing like them amongst the products of volcanic action at the present day, and we shall therefore leave consideration of them until we have glanced at those intrusive masses the origin of which is most apparent.

Necks.—The vents from which many of the flows and tuffs that occur in this and other countries where volcanic action has long been extinct, do not now exist as crateriform hollows. Our volcanic areas have been subjected to great denudation, so that what we now behold are only the fragments of volcanic hills and mountains. The upper parts of the cones have been all swept away, and merely their stumps remain. The throats or necks of the old volcanoes are laid bare, but they are plugged up. And as the rocks of such plugs are often much harder than the masses that surround them, it frequently happens that the former rise up abruptly as isolated knolls or hills. By a *neck* therefore we under-

stand a more or less cylindrical funnel or volcanic vent, filled either with crystalline or fragmental materials, or with both. Such necks occur under various circumstances. Sometimes they are the roots, as it were, of little isolated puys or small volcanic cones, from which tuff and lava, or in some cases only loose ejectamenta, have proceeded. At other times they occur in the midst of old lava-fields, and seem to have been the foci from which numerous flows and much fragmental matter have issued.

In fig. 109 we have a section across one of the little puy-like vents, which are so common a feature in some parts of the Scottish

Fig. 109.—NECK FILLED WITH AGGLOMERATE.

Fig. 110.—NECK OF AGGLOMERATE TRAVERSED BY DYKES AND VEINS OF BASALT.

Fig. 111.—NECK PLUGGED UP WITH BASALT.

lowlands. This vent is represented as plugged up with agglomerate—a confused mixture of fragments of volcanic and sedimentary rocks, which not infrequently shows a kind of rude arrangement, the stones and blocks seeming to dip in from all sides towards the centre, where also the larger fragments tend to gather. In some cases the agglomerate may consist almost entirely of volcanic rock-fragments, but as a rule these are largely commingled with pieces of sandstone, limestone, shale, etc.; occasionally, indeed, the whole contents of the neck are composed exclusively of the débris of sedimentary rocks. Now and again the agglomerate of a neck is associated with finer-grained tuffs, and these may even predominate; but this is exceptional. Very often veins and irregular intrusions of basalt or other crystalline rock (fig. 110) pierce the agglomerate. Not infrequently such intrusions seem to occupy the central and larger portion of the neck, and now and again the neck is entirely filled with crystalline rock (fig. 111). The rocks forming the walls of a neck often present the appearance of having been bent over or dragged down into the funnel, and occasionally they have been more or less altered, as if from exposure to heat. Thus sandstones may have a baked and fused aspect; shales may be hardened and

porcellanised, limestones calcined, and coals converted into a kind of coarse coke and sooty substance, the alteration extending occasionally for many yards away from the neck. In other cases little or no change has been produced, coals having sometimes been mined in good condition close up to the walls of a neck.

Volcanic necks of the kind described are distributed in considerable numbers over the Scottish lowlands, more particularly within the areas occupied by the Carboniferous and Permian strata. They are of all sizes, some measuring only a few yards across, while others are several hundred feet in diameter. Sometimes they have come up along lines of dislocation; at other times they have no connection with faults—the vents appearing to have been formed simply by the bursting and blowing out of the strata. They probably resembled in appearance the puys of Auvergne. In most cases the cones seem to have been composed entirely of fragmental materials; but from some of them a stream of lava has flowed, and as many are plugged up with basalt it is probable that this was the case

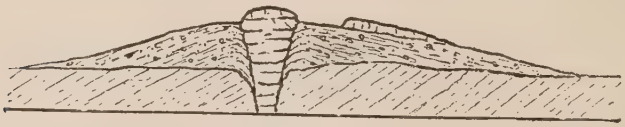


Fig. 112.—NECK FILLED WITH BASALT, AND SURROUNDED BY ACCUMULATIONS OF AGGLOMERATE AND TUFF: REMAINS OF A BED OF BASALT OVERLYING THE TUFF.

with others, although no trace of such coulées may now exist, for as a rule the entire upper portions of the cones have been denuded off. Occasionally, however, we find something more than the mere throats of the old puys—the fragmental matter ejected from these spreading over a considerable area round the central neck, so as to form a kind of low flattened cone (fig. 112). Many of these old Scottish puys are so small that they were probably the result of only one single eruption. Others may have continued much longer in activity, while many may have emitted heated vapours for a long time after they had ceased to discharge lava and loose ejectamenta. In this way we might account for the highly altered condition of the rocks adjoining some vents. After these latter had become choked with débris, heated vapours may have continued to rise up through this material; and it is probably owing to their action that the tuffs and agglomerates are sometimes so highly altered as to have acquired a crystalline texture. When a puy became extinct, the loose fragmental matter forming the cone would tend to be swept down into the vent. At the same time the walls of the neck itself would be more or less exposed to weathering, and

fragments becoming dislodged would fall away, and thus the material accumulating in the vent would acquire a rude kind of arrangement, the débris dipping in on all sides towards the centre. Again, the mouldering of the more readily weathered rocks in the walls of the neck would gradually undermine the harder strata and cause these to bend over into the funnel; and after the neck had become filled up, the subsidence of the consolidating débris would likewise tend to drag down the walls and intensify the inward dip or inclination of the surrounding strata.

The necks now described belong to very different geological ages, some of them pertaining to the Old Red Sandstone and others to Carboniferous and Permian times.

Another set of necks are associated with hill ranges of various volcanic rocks in such a way as to suggest that they were the foci from which those volcanic rocks were ejected. The necks of this class are generally larger than those of the puy-like foci described above, and they are usually, but not always, occupied exclusively by crystalline rocks. Sometimes several occur in the same neighbourhood; at other times they are more or less isolated. They are either circular, elliptical, or irregular in outline, and vary much in size, some measuring less than 100 yards across, while others exceed one mile in diameter. Some fine examples occur in the neighbourhood of Dundee, such as Dundee Law, Balgay Hill, Rossie Hill, Black Law, etc. The rock of these hills is always some variety of basalt (diabase or melaphyre) and is usually macro-crystalline, but sometimes finer-grained. These rocks seem to form the stumps of one or more great volcanic vents from which many of the andesitic and basaltic lavas (porphyrites, melaphyres, and diabases) of the adjacent Sidlaw Hills and Ochils were ejected. Similar necks occur in the Ochil Hills to the west of Kinross, and they are met with also in the Braid Hills, in

Fig. 113.—DIAGRAMMATIC SECTION ACROSS THE VALLEY OF THE TAY, NEAR DUNDEE.
s, Old red sandstone, etc.; *l*, lava-form rocks and interbedded conglomerates, etc.; *sh*, intrusive sheets; *N N*, necks filled with diabase, etc.

the volcanic hills of Ayrshire, and elsewhere. The strata through which they come are often much jumbled and broken, and intersected by great intrusions of volcanic rock which seem to proceed from the necks. But it is noteworthy that the rock in those lateral intrusions often differs in character from that which occupies the necks. In the neighbourhood of Dundee (see fig. 113), for example, the rock in the necks is commonly a dark bluish grey coarsely crystalline diabase, while that of the irregular sheets and veins proceeding from the necks is usually a light-coloured highly felspathic rock in which pyroxene is not nearly so abundant, the rock consisting principally of plagioclase. There can be no doubt, however, that both rocks have proceeded from the same molten magma, for all gradations of structure and mineralogical composition can be followed in one and the same rock-mass. Occasionally patches of volcanic fragmental rocks are found adhering to the rock of these necks; and now and again such materials occur in greater abundance, as in the Braid Hills, where a large neck is composed of felsitic tuff.

There can be little doubt that the necks of the kind just described represent upon the whole a more extensive volcanic action than is shown by the smaller puy-like eruptions already referred to.

Intrusive Sheets.—Mention has just been made of lateral intrusions proceeding from certain necks. Such intruded masses, when they conform in their direction more or less closely to the bedding of the strata amongst which they occur, are spoken of as *intrusive sheets*. In many cases such intrusive sheets, however, have no apparent connection with any old volcanic vents. They are met with very abundantly in Scottish palæozoic strata, more especially in the Carboniferous areas. In petrological character they often do not differ at all from rocks which have flowed out at the surface as lavas. They are, however, upon the whole, more generally macro-crystalline, and are never slaggy and scoriaceous, although now and again they may contain vesicular areas, especially towards their upper surface. Not infrequently they show columnar structure, the columns being arranged, as in contemporaneous flows, at right angles to the planes of cooling. The strata amongst which they lie are often more or less altered at the line of junction, both underlying and overlying strata being affected, but the latter most markedly. Very often portions of the adjacent rock are caught up and enclosed in the igneous rock. In some cases the heat evolved from such intrusive sheets has rendered the coals in overlying strata anthracitic at a distance of several fathoms. Such alterations of strata overlying an igneous rock must be taken as

good evidence of the intrusive character of the latter. Although some intrusive sheets keep to the same general horizon over wide areas, yet closer examination will usually show that sometimes they rise a little above or sink a little below that horizon (fig. 114). Frequently they break across the strata and continue their course along some different horizon, which they may leave after a while for another level, by again cutting across intervening strata. The molten matter has been forced up from below along lines of weakness, such as faults, joints, junctions of unconformable strata, or sometimes it has risen in pipes or fissures opened by the volcanic forces. And the reason why such intrusions are so frequently found to terminate as sheets more or less conformable to the strata amongst which they lie, is simply due to the fact that bedding-planes were lines of weakness. It was easier for the molten rock to make its way between the beds than to force for itself a passage across them. Very often the sheets are intruded along the line of a coal-seam or bed of limestone, which are either very highly altered or have altogether disappeared, those rocks having been more readily assailed than the much less reducible sandstones, shales, and clays with which they are associated.

Fig. 114.—INTRUSIVE SHEET.

A peculiar form of intrusive sheet has been described by Mr. G. K. Gilbert as occurring in the Henry Mountains of Southern

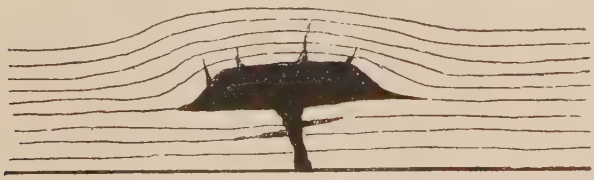


Fig. 115.—LACCOLITE.

Utah. These *laccolites*, as they are termed, consist of trachytic lava which has risen in pipes, but, unable to reach the surface, has forced itself along the bedding-planes, pushing up the overlying strata into dome-shaped elevations (fig. 115).

Amongst the rocks which occur as intrusive sheets are trachyte, basalt-rocks, diorite, felsite, porphyrite, etc.

Dykes and Veins.—Igneous rocks which rise in even-sided vertical wall-like sheets are called *dykes; vein* being the term applied to the more irregular, winding, branching, and generally smaller intrusions. The most characteristic dykes are those of augitic rocks (basalt and its varieties). These vary considerably in thickness, some being less than a foot while others reach 100 feet and more. They vary also very much in length, extending in an approximately straight line from apparently only a few yards up to distances of many miles. Sometimes when they intersect rocks which are more readily denuded than themselves they rise up as wall-like ramparts above the general level of a country; on the other hand, when they traverse rocks less yielding than themselves, they frequently form deep clefts or trenchlike hollows. Occasionally a dyke splits up into two or more smaller dykes, and now and again it sends out veins. The termination of one of the larger dykes has not often been observed. In an ironstone pit at Carluke a dyke abruptly terminated in the manner shown in the ground-plan (fig. 116*a*). Sometimes these dykes have come up along lines of faults, but this is by no means general. More frequently they seem to cut across the rocks without any trace in the latter of vertical displacement—the rocks have simply been fractured, and the molten matter has risen and consolidated in the fissure so formed. The dykes generally run in approximately straight or gently undulating lines. This is particularly the case when they traverse areas of sandstone and shale, but when they enter a region composed of crystalline rocks, or of hard rocks like greywacké, their course is apt to be more serpentine or zigzag. Two sets of such basalt-dykes have been met with in Scotland—one of which trends approximately east and west and the other approximately north and south.

Fig. 116*a*.—TERMINATION OF A DYKE: GROUND-PLAN.

Dykes are usually distinctly jointed at right angles to the planes of cooling, so that if the dykes be vertical the best-marked joints will be horizontal. Now and again this jointing gives rise to very fine prismatic columns. In some cases the dykes show a kind of platy structure, the rock being divided into thin sheets arranged parallel to the walls, and occasionally each individual sheet shows an independent prismatic structure (fig. 116). But this structure is not often seen in the larger dykes. The rock of a dyke is generally most markedly crystalline towards the centre, becoming finer grained and often compact towards the sides, which are sometimes covered as it were with a skin of volcanic glass. Towards

the centre vesicular cavities not infrequently appear; sometimes arranged in more or less regular lines parallel to the walls of the dyke, at other times occurring sporadically. Vesicular cavities, generally of much smaller size, are also usually present near the sides, often, like those in the centre, arranged in lines. Such cavities are of course frequently filled with crystalline mineral matter, such as calcite, zeolites, quartz, etc. In some dykes free

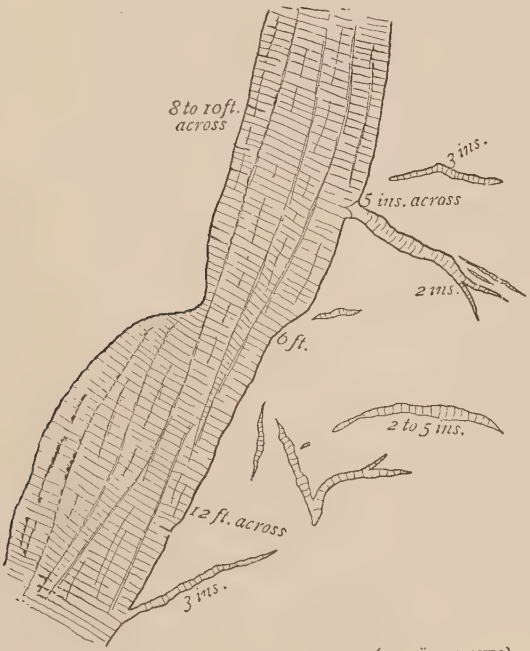


Fig. 116.—GROUND-PLAN OF DYKE AND VEINS (FAERÖE ISLANDS).

quartz occurs in the form of blebs. The vesicular cavities are generally globular or irregular—seldom flattened as in a lava-flow. As a rule the strata are not much affected along the side of a dyke, and the alteration seldom extends beyond a foot or two. In the case of very thick dykes, however, sandstones and shales along the line of junction may be much baked and altered, and coals coked for many yards away from the junction. Now and again the adjoining rocks are considerably jumbled and broken, and large masses are caught up and enclosed in the *marginal areas* of the dykes.

Basalt-dykes of a less regular form are of frequent occurrence,

especially in regions where fissure-eruptions have taken place. Branching and ramifying dykes of this kind are very common in the Western Islands of Scotland, in the Faeröes, and Iceland. Numerous veins proceed from such dykes, as may be seen in the section, fig. 37, p. 80, and the ground-plan in fig. 116.

In some places, as in the Cheviots, the Sidlaws, the hills of Ayrshire and elsewhere in Scotland dykes of fragmental materials are met with. These vary in width from a foot or two up to many yards, but they do not as a rule extend for such distances as many dykes of crystalline rock. They are also never met with except in association with other volcanic rocks—their presence usually indicating the proximity of some volcanic vent. The fragmental materials are generally angular—forming a coarse agglomerate—and may consist entirely of volcanic rocks, or of a mixture of these and sedimentary rocks. In rare cases no fragments of volcanic origin occur. Now and again veins of basalt or other eruptive rock have been intruded into these *agglomerate-dykes*. Such dykes must be carefully distinguished from the *fault-rock* which often occurs along a line of dislocation. The latter is composed of fragments of the adjoining rocks crushed and ground together between the opposite walls of the fault, while the agglomerate-dykes are the result of small eruptions—fractures, formed in the neighbourhood of some volcanic focus which have been filled up with ejectamenta, probably introduced much in the same way as the agglomerate of the necks.

The veins associated with granite, etc., are described later on.

Bosses.—These are irregular-shaped masses of crystalline eruptive rocks, which appear to be for the most part of deeper-seated origin than any of the necks described above. They are composed of such rocks as gabbro, diabase, diorite, trachyte, syenite, quartz-porphyry, and granite. In ground-plan a boss usually covers a much wider area than a neck; and frequently intrusive sheets, dykes, and veins proceed from it in many directions. No hard and fast line, however, can be drawn between bosses and necks. Some of the large masses of intrusive diabase near Dundee, which have been referred to as necks, might just as well be described as bosses. It is probable that many, perhaps most bosses, are merely the more deeply-seated portions of ancient volcanoes—the reservoirs from which molten matter was pumped up to the surface. The rock of a boss is generally coarsely-crystalline, and seldom or never vesicular, save here and there near its junction with the rocks that surround it. It is, moreover, noteworthy that the rock of the dykes and veins that proceed from a boss is usually less basic than that of the boss itself. Again, the latter not infrequently is

traversed by what are termed *contemporaneous veins*—that is to say, veins which are approximately of the same age as the rock they traverse, and these too are as a rule more acidic than the mass through which they ramify.

Bosses are most typically represented by granite; occasionally these granitic bosses are more or less circular in ground-plan—at other times they are quite amorphous. Not infrequently they are well developed along the centre of true mountain-chains, rising up between steeply-inclined strata. In other regions they seem to break across the strata at all angles and to rise through these in the same way as intrusive masses, necks, and bosses of diabase or other igneous rock. Innumerable irregular dykes and veins usually proceed from the granite, and penetrate the surrounding rock in all directions (figs. 117, 118); while many contemporaneous veins ramify through the granite itself. Some of these latter are extremely coarse in texture (pegmatite), others are fine-grained and often differ in character from the granite itself—many consisting of felsite with little or no mica. The veins that proceed from the granite into the adjoining rocks also frequently lose their granitic character and pass into quartz-felsite or quartz-porphyry. The origin of the so-called contemporaneous veins of granite has been long a vexed question, and is still doubtful. By some they are termed *segregation-veins*. They seem to have been formed at a time when the rock was only partially consolidated, for the large crystals of the pegmatite veins indent the surrounding finer-grained granite; and even the micro-crystalline felsitic veins are similarly welded into the rock they traverse. It is not improbable then that these veins

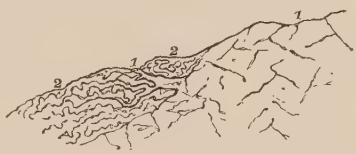


Fig. 117.—1, GRANITE SENDING VEINS INTO CRUMPLED SCHISTS, ETC., 2. (R.)

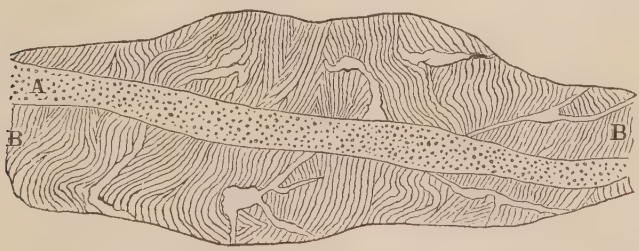


Fig. 118.—A, VEIN OF GRANITE; B, CONTORTED SCHISTS. The ramifying white spaces are white quartz. Arran. (R.)

were injected before the granite had become quite consolidated; and it seems certain that the rock of the veins and the granite itself originally formed portions of one and the same molten mass. It may be, as Mr. Teale has suggested, that the half-consolidated plutonic mass may have been subjected to powerful crushing during some earth-movement, when that portion of the magma which remained liquid, now largely deprived of its basic ingredients, would be squeezed out of the mass, and might finally consolidate as contemporaneous veins in the granite, or as dykes and veins in the surrounding rocks.

Fragments and larger masses of the adjacent rocks are often enclosed in granite, and a zone of more or less highly-altered rocks usually surrounds a granite boss. Indeed, the alterations produced by granitic outbursts are generally much more marked than in the case of other plutonic masses—the adjacent rocks frequently becoming quite crystalline, and losing nearly all trace of their original condition. But consideration of such excessive alteration or metamorphism must be reserved for the succeeding chapter.

It seems highly probable, then, that bosses of granite and other granitoid or coarsely-crystalline plutonic rocks are the deep-seated stores from which volcanoes were supplied with their lavas. The more acidic plutonic rocks agree generally in chemical composition with the acidic lavas, their widely differing petrological character being due to the very different conditions under which they cooled and solidified. In the same way the more basic plutonic masses have their corresponding basic lavas. Although we have still very much to learn we can yet see how greatly our knowledge of vulcanicity has been increased by a study of the sorely-denuded relics of volcanic action in bygone ages. We certainly know a great deal more than we should had our studies been confined simply to what is now taking place in existing volcanoes.

CHAPTER XVIII.

CRYSTALLINE SCHISTOZE ROCKS.

Metamorphism—Foliation—Common minerals entering into composition of crystalline schistoze rocks—Petrology of schistoze rocks—Mode of occurrence and origin of these rocks—Local or contact metamorphism—Regional metamorphism—Archæan schists.

No rock can long retain all the characters impressed upon it at the time of its formation. Sooner or later it undergoes some process of alteration whereby its original character becomes modified to a lesser or greater extent. Many such modifications have come before our attention in preceding pages. We have seen how incoherent sediments become indurated, sometimes by mere pressure, sometimes by the action of percolating water. We have learned also that rocks frequently have been altered at their junction with eruptive masses. Now when such alteration has proceeded so far as to produce a re-arrangement of the constituent elements of rocks and to develop a semi-crystalline or crystalline structure—such extreme alteration is termed *metamorphism*, and the rocks so affected are described as *metamorphic*. Many metamorphic rocks have a massive structure, and in hand-specimens some might readily be mistaken for plutonic rocks; but a large number are distinguished by a peculiar flaky or pseudo-laminated structure which is termed *foliation*. In a *foliated* or *schistoze* rock the constituent minerals are arranged lengthways in alternate lenticular layers which merge into each other, and are usually welded firmly together. The folia are frequently minutely undulating or crumpled and puckered.

Foliated rocks occur under circumstances which leave us in no doubt that they are simply the result of excessive alteration of pre-existing sedimentary or other rock-masses. And the same is the case with certain massive crystalline rocks which seem in like manner to be the result of metamorphic changes. But on the other hand there are extensive regions occupied by similar foliated and apparently massive crystalline rocks, the origin of which is still matter of controversy. We shall therefore describe the rocks in

the first place without any reference to the mode in which they are supposed to have been formed, except where that is obviously suggested by the rock itself, returning afterwards to the interesting question of their origin.

I.—DESCRIPTION OF CERTAIN SEMI-CRYSTALLINE AND CRYSTALLINE BEDDED, MASSIVE, AND FOLIATED OR SCHISTOZE ROCKS.

(*a*) **Mineral Constituents.**—Many of the minerals which enter into the composition of the rocks about to be described have already been mentioned. The most important species are the following:—

Quartz (see p. 143).

Micas: chiefly muscovite and its varieties (damourite, sericite, margarodite).

Felspars: chiefly orthoclase (see p. 144).

Talc: monoclinic; a hydrated magnesian silicate; very sectile, with an unctuous greasy feel; splits into thin *non-elastic* folia.

Chlorite (see p. 148).

Hornblende (see p. 146).

Actinolite: monoclinic; silicate of lime, magnesia, and iron; green; often in long, thin, fibrous, radiating crystals.

These may be considered the most important essential minerals, inasmuch as the rocks composed of them are those which occur most commonly and have the widest distribution. Other essential minerals of less importance are the following:—

Garnet: cubic (usually as rhombic dodecahedrons or icosatetrahedrons); silicate of alumina with a silicate of lime, magnesia, iron, or manganese, etc.

Omphacite: a grass-green, granular variety of pyroxene.

Smaragdite: a peculiar variety of amphibole; lamellar structure; light grass-green in colour.

All the above named species may also occur as accessory minerals. Other accessory minerals of some little importance as giving rise to rock-varieties are—

Andalusite: trimetric; silicate of alumina; often occurs in apparently square prisms.

Chiastolite: trimetric; a variety of andalusite; the crystals when broken across often show cruciform or tesselated patterns, which are due to the presence of impurities; occurs in some slates.

Staurolite: trimetric; silicate of alumina with ferrous oxide,

magnesia, and water; often in twinned cruciform crystals in some slates.

Ottrelite: silicate of alumina with protoxides of iron and manganese and water; occurs in thin hexagonal tables in certain slates.

Many other species occur as accessory minerals in the rocks described below, such as magnetite, schorl, rutile,[1] sphene, and epidote, pyrite, specular iron,[2] etc.

(*b*) **Rocks.**—Quartz-rock or Quartzite: an aggregate of quartz-grains welded together into a hard compact rock. It is usually white or rusty yellow or red in colour and has a splintery fracture. In microscopic slices the grains have a rounded and often semifused aspect, appearing as if they had been agglutinated. The siliceous paste in which the granules are frequently set has usually a crystalline texture, and now and again quartz-crystals are developed in it. The rock not infrequently shows false-bedding, and occurs in strata of variable thickness, often forming mountain-masses. Sometimes quartzite assumes a foliated structure, and contains scales of mica which occasionally form layers. This variety is termed *Quartz-schist*.

Hälleflinta (felsitic schist): a very hard, compact (under the microscope, micro-crystalline) rock; shows various shades of yellow, red, brown, grey, green, or black, which occur in alternating bands; composed of an intimate mixture of siliceous and felspathic matter, with occasionally scales of chlorite or mica; in hand-specimens might readily be mistaken for a compact felsite.

Schistoze Conglomerate: composed of water-worn stones embedded in a foliated crystalline matrix.

Clay-slate: a clay rock, grey, blue, red, yellow, green, purple, or black, in colour, that splits readily into thin plates or slabs, which may or may not coincide with the original planes of sedimentation. The fissile structure is superinduced and is termed *slaty cleavage*. Clay-slates are sometimes semi-crystalline in texture—minute plates of mica and microliths of various minerals being developed along the cleavage-planes. There are many varieties of slate, such as *Roofing-slate*, with perfect smooth cleavage; *Pencil-slate*, a soft but firm rock used for pencils for writing on slate; *Spotted-slate* (*Knoten-schiefer*), containing small concretions; *Whetslate* or *Hone-stone*, a highly-siliceous slate with indistinct cleavage, used for sharpening knives; varieties which are characterised by the plentiful development of scattered crystals of some mineral, such as chiastolite, staurolite, or ottrelite, are termed

[1] Rutile: oxide of titanium; colour, reddish brown; often occurs in needle-shaped crystals.

[2] Specular iron: ferric oxide.

Chiastolite-slate, *Staurolite-slate*, *Ottrelite-slate*, etc. Carbonaceous slates charged with organic remains have given rise to *Anthracitic Slates* and *Alum-slates;* these last owe their alum to the decomposition of iron pyrites diffused in fine particles through the rock.

Phyllite: a schistoze clay-rock, containing a considerable quantity of mica in minute flakes, with a larger or smaller proportion of quartz in grains. The rock passes on the one hand into clay-slate and on the other into mica-schist.

Mica-schist: a crystalline schistoze aggregate of mica and quartz. The relative proportion of these minerals varies indefinitely —sometimes the one and sometimes the other predominating. Varieties appear which are composed almost wholly of mica; and others occur in which the mica plays a very subordinate part. The quartz, which is often granular, is distributed in lenticular layers of very inconstant thickness—thinning off and swelling out abruptly. Sometimes it appears as irregular swollen-shaped lumps round which the folia of mica arrange themselves. The mica is usually muscovite, but occasionally it is biotite, or some other species, not infrequently a hydrous mica which closely resembles talc. Many accessory minerals are found in mica-schist, especially garnets; others are schorl, hornblende, chiastolite, beryl,[1] etc.

Talc-schist: white, yellowish, or greenish; a schistoze aggregate of talc, generally containing also quartz and sometimes felspar. It has a soft greasy or soapy feel.

Chlorite-schist: greenish; a scaly schistoze aggregate of chlorite, usually combined with quartz and sometimes with felspar, mica, or talc. Magnetite is often present.

Hornblende-schist: dark green or almost black; a schistoze aggregate of hornblende; usually containing some felspar, quartz, or mica, either in laminæ or irregularly disseminated. When the foliation of this rock is obscure or wanting we have the variety *Hornblende-rock*. Not infrequently the hornblende is replaced by actinolite, which gives rise to schistoze and massive varieties,—*Actinolite-schist* and *Actinolite-rock*.

Gneiss: a foliated crystalline-granular compound of quartz, felspar, and mica. The quartz is white or grey, and occurs in lenticular layers that vary from a mere line up to bands one foot or more in thickness. The felspar likewise forms folia, and is usually orthoclase, but plagioclase is often associated with it. Frequently the quartz and felspar are intimately commingled. The mica (usually muscovite) occurs in laminæ between the other minerals. The texture of the rock is on the whole not so markedly schistoze as that of mica-schist. In some varieties of gneiss the

[1] Beryl: silicate of beryllia and alumina; blue, green, yellow, or white.

felspar occurs in lentil-shaped swellings = *Augen-gneiss* (eye gneiss) or *Porphyritic Gneiss*. Varieties in composition are *Hornblendic Gneiss*, in which hornblende replaces mica; *Protogine Gneiss*, with talc or chlorite for mica; *Graphite Gneiss*, with graphite instead of mica.

Granulite: a schistoze but sometimes massive aggregate of quartz and orthoclase with garnets. The garnets are disseminated irregularly, and are not infrequently accompanied by kyanite.[1]

Eklogite: a compound of smaragdite and red garnet. Another variety is composed of omphacite and garnet.

Garnet-rock: a crystalline granular aggregate of garnet and hornblende, usually accompanied by magnetite.

Marble: a coarse or fine-grained aggregate of crystalline granules of calcite; white, but many coloured and mottled varieties occur: often rich in accessory minerals, such as mica, garnets, corundum,[2] serpentine, quartz, apatite, fluor-spar, magnetite, pyrites, etc. The rock is usually massive, but occasionally foliated.

II.—MODE OF OCCURRENCE AND ORIGIN OF THE FOREGOING ROCKS.

Of the metamorphic origin of some of the rocks mentioned above there is no doubt. Such is the case with quartz-rock and schistoze conglomerate, which are simply much altered sedimentary rocks that still retain many marks of their original aqueous origin; and the same may be said of most clay-slates and many phyllites. The original condition of the others, however, is not so self-evident. In many cases the mode of their occurrence—their association with rocks of eruptive origin—and the fact that we can often trace gradual passages between them and rocks which are clearly of sedimentary origin, leave us in no doubt that their present crystalline structure has been superinduced. These are examples of *local* or *contact metamorphism*. In other cases no such passages are seen, and the rocks may extend over wide areas without any eruptive masses appearing amongst them; these, according to many geologists, are cases of *regional metamorphism*.

Local or Contact Metamorphism.—It has been stated above that eruptive masses are frequently found to effect some change upon the rocks amongst which they lie. Reference has been made to the fact that coals are occasionally converted into a soft sooty substance, or into coke, or anthracite; sometimes they are even altered into graphite, as near Kirk of Shotts and New Cumnock

[1] Kyanite: a silicate of alumina; colour, pale peacock-blue.
[2] Corundum: anhydrous alumina.

in Scotland.[1] Argillaceous shales have likewise been more or less metamorphosed and changed into a very hard jaspideous rock or porcellanite. Sandstones, again, have been so baked as to acquire the semi-crystalline character of true quartzite ; and in like manner fossiliferous limestones have been rendered crystalline and converted into marble, from which bedding and organic remains have alike disappeared. We have also learned that the fragmental matter occupying certain old volcanic vents has occasionally become crystalline, and, save for included blocks of sandstone, etc., which are still recognisable as such, might readily be mistaken for crystalline eruptive rock. Again, many rocks at their junction with eruptive masses have acquired a prismatic structure. But contact metamorphism on a much larger scale frequently occurs in connection with bosses and amorphous masses of granite and other deep-seated plutonic rocks. Such masses are often surrounded by a zone of metamorphosed rocks which may sometimes reach a breadth of one or two miles. Frequently these rocks assume a foliated structure and crystalline texture, which are always best developed as the plutonic mass is approached. A progressive change may be traced as we follow the strata towards the eruptive rock—beds of clay-slate and greywacké, for example, gradually losing their clastic or fragmental character, and ultimately becoming crystalline schists. Among the first evidence of metamorphism to be noted in some regions is the development in the slates of small knot-like concretions which increase in numbers and size until the rock itself begins to acquire a crystalline texture, when the concretions gradually diminish and eventually disappear, and the rock then becomes entirely crystalline and schistoze—a true mica schist—the foliation being developed along the planes of bedding or of cleavage. The knotted or spotted slates as they approach a plutonic mass often show abundant crystals of chiastolite, and such chiastolite-slates frequently graduate into andalusite-mica-schist. Or we may find greywacké in like manner passing into mica-schist and gneiss. Foliation is thus a common accompaniment of local or contact metamorphism, the schistoze character being gradually developed and becoming more and more pronounced as the eruptive rock is approached, along the borders of which the folia are not infrequently crumpled or puckered. Sometimes, however, in the immediate neighbourhood of a boss of granite foliation becomes obliterated, and it is then difficult to distinguish between the altered and the eruptive rocks.

[1] In the moors near Shotts, where blackband ironstone is calcined in large heaps or "bings," the underlying peat on the removal of the "bings" has been found converted into a coarse prismatic coke to a depth of several feet.

The development of new minerals (contact minerals) in the rocks surrounding intrusive masses is often well seen in marble (altered limestone). In this rock a number of calcareous silicates frequently appear, such as garnet, scapolite, wollastonite, prehnite, epidote, hornblende, etc. In slates again, as already mentioned, andalusite and chiastolite are often developed; and such new minerals may occur in the same rock with fossils, as in the altered Silurian strata to the south-west of Christiania.

Thus we have direct evidence to show that under certain circumstances new crystallised minerals may be developed in clastic rocks, and that these rocks may themselves become crystalline and acquire a foliated structure. From the fact that such changes have frequently been superinduced in the neighbourhood of eruptive masses we must conclude that *heat* is a principal agent of metamorphism. We can hardly believe, however, that dry heat alone would suffice to account for the alteration of masses of sedimentary strata many hundreds or even thousands of feet in thickness. It is probable that water has always played an important part in most metamorphic changes. Water, as we have seen, makes its way downwards by cracks and fissures to great depths, and appears to be diffused interstitially through the mass of all rocks. The presence of this water would enable the heat, derived from an eruptive rock, to pass outwards in all directions, and we can readily understand how the chemical action of the water would favour the rearrangement of rock-constituents. From the eruptive masses themselves highly heated water and vapours would find their way into the pores of the surrounding strata, and might well bring about many mineralogical changes. The constituents of a clay-slate, for example, might become entirely re-arranged and crystallised without the introduction of any new mineral matter, so that the chemical composition of the altered crystalline rock would agree with that of the original unaltered clastic rock. On the other hand, some new constituents might be carried in by percolating water, or by heated vapours, or some portion of the original constituents might be removed by the same agents, and in these ways the ultimately metamorphosed rock would come to differ in composition from the original rock.

Regional Metamorphism.—We have now seen that certain metamorphic rocks occur in connection with eruptive rocks in such a way as to convince us that the intrusion of the latter was the cause of the metamorphism. But there are many wide regions of metamorphic rocks where eruptive rocks are either wanting or appear on too small a scale for us to suppose that they could have been the cause of the alterations. These are cases of *regional metamorphism*. Thus in the South-east Highlands of Scotland we have

a great succession of various clastic rocks, such as pebbly and fine-grained greywackés, greywacké-slate, clay-slate, limestone, etc., which have been metamorphosed in many places into gneiss, quartz-rock, mica-schist, micaceous phyllites, hornblende- and actinolite-schist, marble, etc. Here and there the strata are pierced by granitic masses, but the metamorphism is not confined to the neighbourhood of such amorphous eruptive masses, but extends for many square miles over regions in which no granite is visible at the surface. Where the strata are highly disturbed and contorted the metamorphism is most pronounced, the micaceous phyllites and mica-schists being much crumpled and puckered, and the rocks seamed in all directions with veins of white quartz. Yet such highly altered beds alternate often rapidly with quartzose grits in which the clastic structure is still apparent; now and again too a bed or layer of coarse pebbly conglomerate makes its appearance, while here and there irregular beds of hornblende-rock, diorite, and gabbro occur in such a way as to suggest that these are metamorphosed intrusive igneous rocks. Again, Professor Reusch has shown that in the neighbourhood of Bergen in Norway there occurs a great series of phyllites, mica-schists, hornblende-schists, and chlorite-schists with intercalated beds of gabbro, gneiss, granulite, and conglomerate. Here and there in this series occur lenticular patches of fossiliferous limestone, while fossils of Upper Silurian species, deformed and crushed, are met with also in true mica-schist.

The recent observations of Messrs. Lapworth, Peach, and Horne, on the highly faulted and altered rocks of the North-west Highlands, throw considerable light on the origin of regional metamorphism. In that region the rocks have been powerfully affected by earth-movements—the strata have not only been violently folded back or reversed, but the folds have yielded, and great masses of Archæan and Cambrian rocks have been thrust horizontally over Silurian strata. The result of these movements has been to obliterate more or less completely the original characters of the rocks, and to produce new crystalline structures. Beds of sandstone acquire a foliated structure and crystalline texture, while rocks already crystalline and foliated have had a new set of schistoze planes superinduced in them, the planes of foliation being generally parallel with the surfaces of movement. These changes were brought about by the earth-movements referred to, under which, as the rocks sheared, their individual particles were forced over each other in one common direction. The rocks which occur along the thrust-planes (see p. 200) sometimes present a remarkable streaked appearance that recalls the fluxion-structure of an eruptive rock. Another noteworthy feature of the altered rocks of this neighbourhood is the

development of minerals along the superinduced planes of schistosity, such as micas, hornblende, actinolite, and garnets. From the facts thus briefly stated we learn that metamorphism may be induced in rocks without the aid of eruptive masses. We may well suppose that during powerful earth-movements, when enormous rock-masses are folded, and crumpled, and contorted, or fractured and forced over each other, great heat must be evolved, which, with the aid of interstitial and percolating water, might bring about metamorphic changes over wide regions.

Archæan Schists.—In the foregoing illustrations of metamorphism we have confined our attention to rocks, many of which can be demonstrated to be altered clastic or fragmental rocks. In all these cases the crystalline and foliated characters are clearly superinduced—all gradations being traceable from a rock of undoubted clastic structure into one which is wholly crystalline. But in many countries there exist enormous areas of crystalline schistoze rocks amongst which no such gradations occur. These rocks are always the oldest in the regions where they are met with, the junction between them and the overlying strata being invariably an unconformity. Such are the coarse-grained gneissoze rocks of the Outer Hebrides and Western Ross-shire which are overlaid unconformably by Cambrian sandstones and conglomerates. Similar rocks occur in Scandinavia ; and they are developed on a most extensive scale in Canada and other lands. They are upon the whole more coarsely crystalline than the schistoze rocks described above as of undoubted metamorphic origin. In many places, indeed, foliation is hardly visible, and the gneisses acquire all the appearance of amorphous granitoid masses. Some geologists doubt whether these Archæan rocks are really metamorphic, and are inclined to believe that they were chemical precipitates of the primeval ocean, laid down at a time when the temperature of the water was probably much higher, and when the relative proportion of the mineral substances which the sea held in solution must have differed very considerably from what is now the case. But, as we have seen, some crystalline schists are certainly the result of metamorphism, and we cannot therefore deny the possibility of the so-called Archæan schists being likewise of metamorphic origin. The Archæan gneiss of Sutherland, according to Messrs. Peach and Horne, has in certain places had new planes of foliation developed in it, and this change, as already mentioned, was superinduced by great mechanical movements. Moreover, it is a generally recognised fact that the Archæan schists, all the world over, invariably occur in highly-inclined and contorted beds — they have in short been subjected to those very conditions under which the Silurian strata of the Scottish Highlands

and Southern Norway acquired their metamorphosed character. It is not unreasonable, therefore, to suppose that the Archæan schists are simply highly altered rocks, some of which may have been originally aqueous, and others igneous.

Serpentine, which has been described under igneous rocks as an altered peridotite, is not infrequently associated with the crystalline schists. In such cases it is often interbedded with crystalline limestone. Some have suggested that these bedded serpentines have been precipitated directly from oceanic water; while others think they may have been formed by organic agency in the same way as the glauconite which is so frequently found filling the foraminiferous shells that strew the bottom of existing seas. It is possible, again, as some suppose, that the serpentines in question may have been originally magnesian limestones or dolomites.

Granite, as we have seen, is frequently associated with metamorphic rocks. In many cases it is undoubtedly of eruptive origin, but sometimes it would seem as if the granite itself were metamorphic, since gradual passages can be traced from it into gneiss; or these two rocks may occur in alternating beds. It is simply its foliated structure which distinguishes gneiss from granite, and when this foliated structure becomes obscure or even disappears, as is frequently the case amongst the Archæan crystalline schists, the gneiss becomes petrologically a granite; and the common appearance of veins of pegmatite amongst such coarse-grained granitoid gneissoze rocks recalls the similar veins in eruptive granite. It is by no means improbable, however, that many coarse-grained Archæan gneisses may have been originally eruptive granites which have had a schistoze character superinduced in them by earth-movements, like those which have produced schistosity in the altered rocks of Sutherland. So in like manner hornblende-schist would often seem to have been originally an eruptive rock, such as diorite. At all events it is certain that foliation does not necessarily always coincide either with planes of deposition or planes of cleavage. But we have still much to learn with regard to the origin of the crystalline schists and associated rock-masses. And although it seems probable that all those schists, etc., are simply metamorphosed aqueous and igneous rocks, yet it is not impossible that the "Archæan schists" may sometimes have had quite another origin, and may, to some extent, represent the chemical sediments of a thermal ocean. The weight of evidence, however, so far as it goes, seems at present to be against this view.

CHAPTER XIX.

ORIGIN OF SOME PROMINENT ROCK-STRUCTURES AND SURFACE-FEATURES.

Structure and origin of true mountain-chains—Origin of curvature of strata—Reversed faults and cleavage—Oceanic basins and continental ridges—Association of volcanoes with mountain-chains—Condition of the earth's interior—Regional elevation, normal faults, and fissure-eruptions—Composition of the earth's interior—Surface-features due to denudation.

In describing such superinduced rock-structures as *curvature*, *cleavage*, *faults*, etc., it has hardly been possible to avoid some reference to their origin. It is obvious, for example, that anticlinal and synclinal folds must have been induced by lateral thrusting or pushing; but it is hard at first sight to understand how such lateral movements have come about. Sometimes, indeed, we can see that strata have been folded and crushed by the intrusion amongst them of amorphous masses of igneous rock. The strata, in such cases, have been thrust aside to make room for the eruptive matter. The crumpling induced by such intrusions, however, is quite local; it is confined to the neighbourhood of the eruptive mass. How, then, can we explain the occurrence of folded and crumpled strata in regions where no eruptive rocks occur? And how has it come to pass that in some places sedimentary formations have retained much of their original horizontality, while in other regions strata of the same age have been thrown into broad undulations and sharper folds? In our islands, for example, the Silurian strata are as a rule much folded, and the beds generally dip at high angles; while in Russia the same formation extends in approximately horizontal and undisturbed beds over all the wide region between the Baltic and the Ural mountains. From these and many other similar facts we learn that all parts of the earth's crust have not been subject to the same degree of lateral crushing and squeezing.

Origin of Typical Mountain-Chain.—The phenomena presented by a typical mountain-chain throws no small light upon

Fig. 119.—DIAGRAMMATIC SECTION OF A TYPICAL MOUNTAIN-CHAIN.

the origin of curvature. In the accompanying diagram (fig. 119) only the more prominent features of such a chain are introduced. The section is supposed to be drawn across the mountain-ridges at right angles to their direction. At A the strata are represented as approximately horizontal. As we proceed towards the central ridge B, however, it will be observed that the beds begin to rise and fall in a series of unsymmetrical anticlines and synclines, the folds becoming sharper and closer as we approach B, until at *d* they are actually reversed. It will be further noted that the steeper slopes of the anticlines face the low grounds (A), the gentler slopes being inclined in the opposite direction, *i.e.* towards the central axis of the chain at B. And the same phenomena are repeated on the other side of the axis between B and C. In the centre we have in many cases some crystalline igneous rock, such as granite, or it may be a crystalline schistoze rock like gneiss, and this central mass occasionally shows the fan-shaped structure already described (see p. 184). The mountain-structure shown in the diagram is frequently complicated by the occurrence of faults, some of the most pronounced of which are reversed faults (fig. 101, p. 200)—the anticlinal axes having been broken across, and the strata on the side facing the mountains thrust violently over those on the side of the anticline that looks towards the low grounds. Moreover, slaty cleavage is often superinduced, the cleavage-planes being parallel to the axes of the folded strata.

Such a mountain-chain, consisting of a series of approximately parallel ridges, marks a line of weakness in the earth's crust. Let us suppose that some region of undisturbed strata is slowly sinking.

Now, in such an area great lateral squeezing and crushing must result, from the simple fact that the strata are compelled to occupy less superficial space. Should they be equally unyielding throughout, then folding will take place generally ; but in many cases the lateral pressure will be relieved by unequal yielding of the strata. The strata will tend to give way along a certain line or lines at right angles to the pressure, and crushing will be relieved by the bulging up and folding of the strata in a series of more or less parallel anticlines. And it needs little reflection to become convinced that in such a case the anticlines will present their steeper faces to the low grounds, and that their axes will dip in towards the central axis of the chain. We can further see that it is just in such a series of movements that we should expect reversed faults to occur—the sharply-folded strata will now and again crack across, and one limb of an anticline will be shoved over the other (fig. 101). The intense pressure to which the rocks are subjected will likewise quite account for the occurrence of slaty cleavage; and the frequent appearance of metamorphism amongst the rocks of such mountain-chains is just what we might expect.

When the lateral pressure, induced by a movement of subsidence, is relieved by the more or less general folding of the strata throughout the subsiding area, then no mountain-chain will result, but the rocks will simply be thrown into a series of normal anticlines and synclines, and the direction of these will be modified according to the regularity of the subsidence.

Origin of Oceanic Basins and Continental Ridges.—Of late years the belief has been gaining strength that the oceanic basins and continental ridges of our globe are of primeval antiquity—that their origin is older than that of our oldest sedimentary formations. They are believed to be simply great flexures in the earth's crust, caused by the gradual sinking-in of that crust upon the slowly cooling and contracting nucleus. If this be the case, then the continents bear to the oceanic basins much the same relation as a mountain-chain does to the low grounds that adjoin it. As we shall afterwards learn, none of our sedimentary formations is of abysmal origin—on the contrary, most of the aqueous strata that compose our dry lands have been laid down in comparatively shallow seas. But although it can be proved that many oscillations of level have taken place at successive periods within each continental area, by which the extent and outline of the land have been modified again and again, yet the great continental ridges would appear to have persisted, from the earliest geological times, as dominant elevations of the earth's crust. Some portions of these, as Professor Dana remarks, may have been submerged for thousands

of feet, but the continents have never changed places with the oceans. The position of the great mountain-chains of the globe favours this view of the permanency of oceanic basins and continental areas. We find that those mountains extend along the marginal areas of the continents, and that, to use Dana's expression, "the highest mountain-border faces the largest ocean." Now, this arrangement would naturally follow from the depression of the earth's crust within the oceanic areas. Intense lateral pressure would, under these circumstances, be exerted against the continental borders, and the strata there would be squeezed, folded, fractured, and uplifted; and the degree of folding and uplifting would be in proportion to the extent of the sinking area—the highest mountain-chains would face the largest oceans. The same theory accounts for the fact that the strata of maritime regions are generally more folded than those which occur towards the centre of a continental area. In Europe, for example, we find that the Palæozoic and Mesozoic strata of the west and north-west regions are more disturbed than the equivalents of the same formations in Russia. Moreover, the evidence shows that such earth-movements consequent upon contraction of the crust have happened at many successive periods in the world's history, and that not infrequently they have taken place contemporaneously over vast regions of the earth's surface.

Association of Volcanoes with Mountain-Chains.—Another point in connection with this subject is the frequent association of volcanoes with mountain-chains—especially with those that occur along the borders of the greatest oceans. It is impossible to avoid the conclusion that this association is not accidental, but that the volcanoes are due to the same causes that produced the chains along which they are distributed.

Condition of the Earth's Interior.—The phenomena referred to necessarily suggest the question—What is the condition of the earth's interior? Several views have been put forward by physicists, the more generally received opinion being that the earth is a solid globe. Those who support this view maintain that if the earth were not practically solid, but consisted of a fluid nucleus enclosed within a thin external shell or crust, the globe would be subject to deformations—would, in fact, be pulled out of shape by the attractions of the sun and moon. No tidal motion could then take place in the sea, for the thin crust "would simply carry the waters of the ocean up and down with it"—the land and sea would rise and fall together, so that there would be no sensible tidal movement of the waters. It is inferred, therefore, that since oceanic tides do exist, the earth must either be solid to the core, or,

if fluid internally, must possess a crust not less than 2500 miles in thickness. Other physicists, however, doubt whether a rocky crust is sufficiently elastic to rise and fall under the attractions of the sun and moon. "Instead of oscillation," as Professor Green remarks, "there might be a slow dragging, first in one direction and then in the opposite direction, so that the average shape would be unaltered, and the changes that did take place might be of a totally different character from oscillations." The existence of volcanoes and thermal springs shows us that a high temperature exists beneath the crust, and similar evidence is furnished by borings and mines. The mean of many observations shows that the temperature increases 1° Fahr. for every 54 feet of descent, so that if the temperature at the surface be 50°, the boiling-point of water (212°) will be reached at the depth of about a mile and a half. It is evident, then, that the heat at a comparatively short distance from the surface would be sufficient at that surface to melt all the rocks, minerals, and metals with which we are acquainted. It is supposed, however, that the substance of the interior is kept in the solid state by pressure. Whenever this pressure is relieved the solid matter will assume the fluid state, and such relief would take place along a line of mountain-elevation, the liquefied mass being squeezed out during the folding of the rocks, and forced upwards through fissures by the action of the imprisoned steam, which is so universally present in lavas. It is very difficult to see, however, how great depressions and elevations of the crust, with all the phenomena of mountain-chains and the foldings and undulations of strata generally, could take place in a solid globe. The impossibility of reconciling the geological facts with the physical theory of the earth's solidity, as upheld by Mr. Hopkins, Sir William Thomson, and others, has led to another view which has been well supported by Mr. Fisher. According to this geologist a liquid substratum separates the crust from the solid nucleus. This view may be looked upon as a compromise between that of a solid globe, as maintained by Thomson, and the older view of a fluid globe enclosed within a thin shell or crust. Notwithstanding the admirable reasoning which physicists have brought to bear upon this subject, it cannot be held as proved that the earth is solid. We do not know all the conditions of the problem, and until these are ascertained the most elaborate mathematics cannot be relied upon to give us a true solution. So far as geological facts go they are opposed to the view of a solid globe or of an enormously thick crust, and in favour of the older hypothesis of a thin crust enclosing a liquid or viscous interior. It is unnecessary, however, to suppose that the crust is sharply marked off from the nucleus. For

all that we can tell there may be a gradual passage downwards from the consolidated matter of the exterior into the semi-consolidated and viscous interior. And the solid crust may moreover be of very variable thickness. With a globe of this kind we can readily conceive how contraction of the earth as a whole would cause the crust to become corrugated. If we take the basin of the Pacific to be a primeval area of depression, and the great mountain-chains that overlook that sea to owe their origin to continued sinking of the crust underneath the adjacent ocean, it is possible that the volcanic eruptions of that vast region may be due to the same cause. The viscous-liquid matter of the interior will be displaced underneath the sinking area, and an equivalent weight will be forced up through fissures in the elevated mountain-chains, and continue to be discharged until equilibrium is recovered.

Origin of Regional Elevation, Normal Faults, and Fissure-Eruptions.—Reversed faults, as we have seen, can hardly fail to occur where there is much plication and inversion of strata; they are one of the natural results of intense lateral pressure. The origin of *normal faults—i.e.* faults which hade in the direction of downthrow—is a harder problem. Faults of this kind traverse alike horizontal, undulating, or highly-contorted strata. But in regions of highly-inclined and inverted strata they almost invariably prove to be later than the plication of the strata and the reversed-faults of such regions. It is hard to see how a normal fault crossing horizontal strata can be due to lateral pressure. Such pressure exerted upon horizontal beds that did not yield by folding would no doubt result in the rupturing and dislocation of the strata; but the faults thus produced would be reversed—the hade would not be in the direction of downthrow. But on the hypothesis that the crust is only a thin shell inclosing a viscous nucleus, it is conceivable that we might have wide regional elevation without much lateral crushing. Great depression taking place over the bottom of an oceanic area would produce crushing and pressure upon the borders of adjacent continents; but it might at the same time cause a general bulging up in the interior of the continents—the viscous matter underneath the marine areas being subject to enormous pressure, might be displaced and so raise the level of the liquid mass underlying the land, and thus cause a widespread upheaval. We know indeed that certain regions of the earth's crust have undergone such general elevation, the land appearing as if it had been pushed up bodily from below. If such bulging-up of the crust have taken place, then the strata over the rising area would be subject to tension, and this, if sufficiently great, would result in rupture and dislocation. One or more series of

fissures would thus be formed, along which displacement would occur. Those segments of the ruptured strata which had the broadest base and therefore exposed the largest surface to the pressure from below, would tend to rise more than the segments which had narrow bottoms. These latter, therefore, would afterwards appear as if they had sunk down relatively to the adjoining broader segments. In other words, we should have the phenomena of normal faults produced (see fig. 120).

The same hypothesis, that of thin crust and liquid interior, helps us to conceive how *fissure-eruptions* may take place. For if

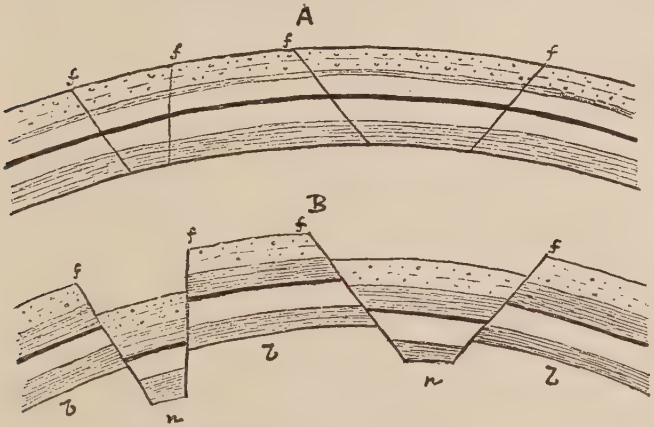


Fig. 120.—ORIGIN OF NORMAL FAULTS.

A, A segment of the earth's crust subjected to tension during elevation, and cracked along the lines *f f*; B, same area showing subsequent displacement along the lines *f f*; the narrow-based portions *n n*; the broad-based portions *b b*.

there be any abnormal degree of depression of the crust over some particular areas, there will most likely be some corresponding but less amount of elevation in intervening regions, the strata will be pushed up and fractured; and through the fissures thus opened the internal viscous matter might now and again rise and flood wide areas, giving rise to vast successions of lava-sheets like those of our Western Isles, the Faeröe Islands, Iceland, Western North America, the Deccan, etc. In this view the interstitial steam or water-gas, which plays so important a part in volcanic eruptions, is not the inciting cause of activity. Its presence renders the viscous matter more liquid, and its expansion doubtless increases the force of volcanic eruptions; but the extrusion of lava from the fluid or viscous interior would take place even if no steam were present. But as

steam is invariably present in volcanic discharges, and as it could hardly have been derived from the supposed fluid or viscous interior, it is possible, as has been suggested, that the lava in its upward progress absorbs water from that copious supply which is always circulating through the rocks of the crust. All these, however, are merely guesses; and although the geological facts seem to be best explained by the doctrine of a thin crust over a liquid interior, it must yet be admitted that no positive opinion is possible in the present state of our knowledge. We have still to learn what is the true condition of the earth's interior.

Composition of the Earth's Interior.—The weight of the whole earth is computed to be about five or six times that of an equal bulk of water; while the average density of the materials which compose the crust (so far as that is accessible to observation), is only two and a half times that of water. In other words the mean density of the globe is twice as great as that of the crust. It is probable that the density increases with the depth from the surface, and so, of course, must pressure. Possibly, therefore, the greater density of the interior may be due to pressure alone. It is more probable, however, that this greater weight may arise from the presence in the interior of a preponderance of metals. If the doctrine of a thin crust and molten interior be true, then the lavas which are extruded at the surface will give us the composition of the viscous matter which immediately underlies the crust. And the essential similarity in composition of lavas belonging to all ages, and occurring in all quarters of the globe appears to lend support to this view.

Surface-Features due to Earth-Movements, modified by Denudation.—From the account given in chaps. ii.-ix. of the work performed by denuding agents the student will readily understand how the features which have been stamped upon the earth's crust by subterranean action, are all more or less profoundly modified. The corrugated strata of mountain-chains have been intensely denuded, carved, chiselled, hewn, fractured, and pulverised by the various agents of surface-action—rain, running water, snow, frost, and ice. In the case of many mountain-chains we know that they have been alternately elevated and depressed. Squeezed and ridged up at first to a height of several thousand feet, they have been subjected to intense denudation; and, again depressed, their worn and eroded rocks have been covered by newer accumulations of aqueous sediments. Once more they have been upheaved, and the newer strata tilted upon their flanks have in their turn been furrowed and eroded; and this process has been repeated again and again. Thus many mountains of elevation testify to the

activity of the denuding agents during prolonged and widely-separated periods; and of not a few it may be said that they are the mere wrecks of what they must formerly have been. So, again, volcanoes, when they become extinct, tend to be degraded and washed down. In our own country low hill-ranges now represent all that remains of what were once considerable volcanoes, rising to heights of several thousand feet, and covering areas many square miles in extent.

Surface-Features due to Denudation.—There are many mountain-regions in which it is obvious that the mountains are not due to elevation, but are simply monuments of denudation; they stand out as prominences because the rocks which once surrounded them have been worn away. Thus the Scottish Highlands and Southern Uplands are merely elevated plateaux in which deep valleys have been excavated by running water, etc. And the same is the case with the mountains of Norway and many other regions;

Fig. 121.—*a a*, Upper Cretaceous, chiefly chalk, forming the North and South Downs; *b b*, escarpment of Lower Greensand with a valley between it and the Chalk; *c c*, Weald clay, forming plains; *d*, hills formed of Hastings sands and clay. The chalk, etc., once extended across the country, as shown by the dotted lines. (R.)

they are only the remaining portions of more or less continuous plateaux. How enormous the denudation has been we may see by estimating the thickness of rock which has been removed from the tops of anticlines (fig. 121). In this way it can be shown that sheets of rock thousands of feet thick have been gradually removed from the surface of the land. Faulted strata in the same way afford impressive evidence of denudation. Some dislocations are vertical displacements of several thousand feet, and throws of less amount are innumerable; yet many of these give rise to no marked surface-features—the rocks on the high side of the faults have been planed away. It is not too much to say that the present surface of the dry land has been everywhere modelled by the tools of denudation. Hence it is that in regions composed of durable and less durable rocks, the latter are worn away most readily; they form the valleys and low grounds, while the more durable rocks stand up as escarpments, hills, and ridges. Again some rock-structures favour denudation, and others tend to withstand it. Thus it most frequently happens that anticlinal axes instead of forming hills give rise to valleys; while synclines correspond, as a rule not to valleys but to hills. The reasons are obvious, for an

anticlinal arrangement and the jointing of the strata favour the action of the denuding agents ; springs, frost, etc., tend to undermine the beds and to produce landslips. In the case of synclinal strata, on the other hand, the structure has just the opposite effect—there is no tendency to landslips, the beds dipping towards and not away from the axis. The influence of joints in denudation has already been explained (see p. 83) ; the forms assumed by sea-cliffs, river-cliffs, and mountains are determined to a large degree by the nature of the division-planes which intersect the rocks. Thus, the features impressed upon a country by denudation depend partly upon the composition and texture of the rocks, and partly upon their structure as rock-masses. Glacial action tends generally to smooth away all asperities, which are the result of aqueous and sub-aërial erosion, and to produce a monotonous outline ; countries which have been severely glaciated presenting usually a flowing or undulating and rounded configuration.

Table-lands and plains are wide tracts of level or undulating country—the term *table-land* or *plateau* being applied to those which attain some considerable elevation (1000 feet or more), while those that occur at lower levels are called *plains.* Some table-lands are composed of approximately-horizontal sheets of rock, which may be of aqueous or of volcanic origin ; others, however, consist of more or less highly-contorted rocks which have been worn down or truncated by denudation. Both kinds of plateau are usually traversed by valleys which have been excavated by running water, and sometimes they are so highly denuded that their plateau-character becomes obscure, and they present the appearance of irregular ramifying mountain-masses, as is largely the case with the plateau of the Scottish Highlands. Plateaux formed of aqueous rocks owe their elevation to upheaval, those which are built up of approximately-horizontal beds being termed *plateaux of accumulation ;* while those which consist of contorted strata planed down to a level, are known as *plateaux of denudation.* Plains are only less-elevated plateaux of accumulation ; among the most characteristic examples are the wide deltas of the greater rivers. These of course are all of recent geological age, and are approximately flat. But the term is extended to such low-lying regions as Central Ireland, the Midland districts of England, Middle Europe, etc.—regions which have no great elevation and present a gently-undulating surface, interrupted now and again by isolated hills and lines of escarpments and cliffs. Such low-lying areas are composed principally of aqueous rocks, arranged in gently-undulating or approximately horizontal strata, the hills and escarpments marking the outcrops of the harder or less readily-eroded rocks. All these

surface-features are evidently the result of sub-aërial and not marine denudation.

Plain of Marine Denudation.—The sea tends to produce round all coast-lines a horizontal plane. If we suppose a flat tract of sea-bottom to be slowly upheaved, it is obvious that every portion of the rising surface will be subjected to the action of the waves and breakers while it is emerging. Upheaval will take place most likely along some particular axis, so that the form of the new-born land, we shall suppose, is somewhat elongated, its surface sloping gently seawards in opposite directions from the central ridge or line of maximum elevation. In the production of a plane of marine denudation, therefore, two forces are at work—upheaval and the sea—the latter of which tends to modify the surface that would result from upheaval alone. Plateaux of denudation are supposed by some geologists to be simply old planes of marine denudation, profoundly modified, as every old land-surface must be, by sub-aërial agencies.

Thus, while we may reasonably conclude that oceanic basins, continental ridges, and true mountain-chains are corrugations, bulgings, wrinkles, and creases of the crust produced by the sinking-down of that crust on the cooling and contracting interior, we must admit that the present surface-features of the land are due to denudation, and chiefly to the action of the sub-aërial agents. In our own islands we have no true mountain-chains—all our hills and mountains rise above the average level of the ground, not because they have been ridged up from below, but simply owing to the more durable nature of their component rocks. Our mountain-regions are merely much denuded plateaux, and the same is the case with the high grounds of many other countries. Even the youngest mountain-ranges of the globe have been more or less profoundly modified by sub-aërial denudation. We see, then, that marine erosion has apparently had but little to do with the formation of the surface-features of the land. Plateaux of denudation may be partly the result of marine action upon a gradually emerging land-surface. But, on the other hand, such plateaux may simply be old land-surfaces which have been planed down to the level of the sea by sub-aërial erosion, and again upheaved. Give the sub-aërial agents sufficient time and they must eventually plane down any land-surface; the mountains will be moved particle by particle into the sea, and gently undulating plains and flats will take their place. However effectual marine erosion may be, there can be no question that the land is worn away more rapidly by sub-aërial denudation; for whereas the action of the sea is necessarily confined to a narrow belt, that of the

sub-aërial agents has no such limitation. The whole surface of a country is exposed to attack, and the loose material swept downward by rains and rills, by streams and rivers, to the sea must greatly exceed in amount the waste of the coast-line by waves and breakers.

CHAPTER XX.

PALÆONTOLOGICAL GEOLOGY.

Fossils; physical and climatic conditions deduced from; relative age of deposits determined by—Rocks containing same fossils not necessarily synchronous—Gradual extinction of species—Breaks in succession—Imperfections in the record—Orderly succession of changes—Systems—Historical geology—Divisions of strata.

Fossils.—The student has become familiar with the fact that some rocks contain remains of once living creatures. These are called *fossils.* They consist for the most part of the harder and more durable portions of animals and plants, such as bones, shelly coverings, teeth, scales, bark of trees, and tough ligneous tissues. Now and again, however, delicate insects and tender and fragile plants are met with. It is usual to extend the term fossil to even the *casts* or *impressions* of such remains, and to foot-marks and tracks, whether of vertebrates, molluscs, crustaceans, or annelids. The organic remains occurring in rocks have usually undergone some chemical change. They have become *petrified* in whole or in part. The gelatine which originally gave flexibility to some of them has disappeared, and even the carbonate and phosphate of lime of the harder parts of animals, and the woody matter of plants have often been replaced by mineral matter, such as calcite, silica, pyrite, gypsum, etc. So perfect is the petrifaction in some cases that the most minute structures have been preserved, the original matter having been replaced molecule by molecule. The petrifying process, however, is not often so complete as this. Frequently, indeed, it is merely a cast of the harder parts which has been preserved; and it is only rarely that any portions of the internal softer parts of molluscs and crustaceans, for example, have been petrified. After their burial in sediment organic remains generally become decomposed, their elements passing away into the surrounding matrix so as to leave an empty mould, which in very many cases has been subsequently filled up with mineral matter, introduced in solution by permeating water. Thus a large propor-

tion of our fossils are merely pseudomorphs or casts in calcite, silica, pyrite, or other mineral substance. Again, many fossils, such as shells, were filled up at the time of their entombment with sediment, and subsequently the shells have been removed by percolating water, so that what now remains is merely a cast in clay, mudstone, or sandstone, etc., of the interior of the shell—a cast often lying loosely in its cavity, like a nut in its shell.

As a rule, fossils occur most abundantly and best preserved in calcareous and argillaceous rocks, while in porous rocks, like sandstone, they are generally poorly preserved and not so plentiful. One reason for this is that sandstones are more pervious by water, and therefore any organic remains they may contain are liable to be destroyed; but there are other reasons for the comparative paucity of fossils in such deposits, as we shall see presently.

Physical and Climatic Conditions deduced from Fossils.—Organic remains are either of terrestrial, fresh-water, brackish, or marine origin, and are therefore of the utmost value to the geologist who wishes to discover the various changes in the distribution of land and water which have taken place in the past. More than this, they will often afford him evidence as to former climatic conditions. When the fossils belong to living species conclusions as to climate are readily drawn. Thus when we observe in our own country certain beds of clay charged with the remains of an arctic marine fauna, we are compelled to infer that formerly these lands must have been to some extent submerged under the waters of a sea as cold as that which now washes the shores of Arctic lands. But when we come to deal with fossils that belong to wholly extinct species we cannot be so sure as to the climatic conditions under which such species flourished. Sometimes, indeed, we might reason from the analogy of the present and come to some more or less reasonable conclusion. Thus, if we should encounter in some strata many reef-building corals, and if associated with these we should find a number of large chambered shells, together with the remains of arborescent ferns and cycads, which, from their excellent state of preservation, had evidently not travelled far, we should have good reason to conclude that the strata in question had been laid down in the waters of a genial sea, and that the land, which probably existed at no great distance, in like manner enjoyed a genial climate. Again, should we find that certain strata, characterised by the presence of some particular extinct fauna and flora, occur not only in low latitudes (30°-40°), but also within the Arctic Circle, we should be inclined to conclude that such a fauna and flora must have flourished under temperate conditions of climate. When we deal with extinct faunas and floras

in this broad way we are not likely to go far astray, but we might readily do so were we to confine our attention to single fossils. Thus, many years ago bones and tusks of a large extinct species of elephant were found in great numbers in some superficial deposits in the extreme north of Siberia. Now judging from analogy it might have been, and indeed was, inferred that the presence of these remains betokened for Sibera in former times a climate like that of India or Africa. It was subsequently ascertained, however, that the Siberian elephant was provided with a thick coat of wool and hair—a protection suggestive of a cold-temperate climate, like that which is affected by living fur-bearers.

Just as we reason from analogy when we are dealing with questions of climate, so we do with regard to the depths of the sea in which marine fossiliferous strata have been accumulated. Every one knows that the fauna and flora of the sea are influenced by its depth—the animals and plants of littoral regions differ from those whose habitat is in deeper water. If all fossils were of living species we should have no difficulty in ascertaining what beds were deposited in deep and what in shallow water. But when we are dealing with extinct species we are left more or less to conjecture, and will probably be influenced in our conclusion by the general aspect of the fossils, and the nature of the deposits in which they occur. Thus, littoral deposits will generally be coarse-grained (conglomerate, grit, sandstone, etc.); while accumulations laid down in deeper water will consist for the most part of finer-grained materials (clay, silt, shale, chalk, limestone, etc.). Again, in trying to account for the paucity or absence of fossils in certain aqueous rocks we shall have regard to the analogy of the present. Some portions of the sea-bottom, as we know, are not so prolific in life as others—where, for example, there is rapid sedimentation, or where sediment is being constantly washed to and fro upon the bottom, molluscs and other creatures do not appear in such numbers as where there is less commotion, and a slower rate of sedimentation. Yet, again, we must consider whether the character of the strata may not betoken deposition in a salt lake or inland sea; prevalent reddish or parti-coloured tints, and the occurrence of layers of gypsum, anhydrite, rock-salt, or magnesian limestone might be taken as highly suggestive of deposition in water which could hardly have supported an abundant fauna. Brackish-water strata may sometimes be marked by the presence of dwarfed and distorted fossils, which we know to be such by comparing them with the better developed forms that occur in true marine beds appertaining to the same set of strata. Both brackish-water and fresh-water beds are apt to be less fossiliferous than deposits of the

same mineral character which have been accumulated in the sea. But there are many exceptions to this rule. Not infrequently it is hard to say why certain marine strata should be unfossiliferous. Their general character seems often to bespeak quiet sedimentation, and does not differ from that of similar strata which in other regions are abundantly charged with organic remains. In some cases the fossils may have existed and may subsequently have been removed by percolating water. But this explanation will not account for all cases. The fossils are often absent simply because they never were present.

Fossils determine the Relative Age of Deposits.—As already remarked, fossils often belong to extinct species and genera —some of which are closely allied to living forms, while others depart widely from any existing types. And when we come to examine the various assemblages of fossils which occur in separate groups of strata, we are often struck with the strong contrasts that obtain between the several faunas and floras of these separate groups. The cause of this lies in the simple fact that the fossiliferous strata belong to different ages—some are much older than others. The fact that strata belong to more than one period of deposition has indeed already been demonstrated by the physical evidence. We know that in a series of conformable strata the lowest members must be the oldest. This is the *law of superposition*, and it forms the base of all systems of geological chronology. We know, further, that the process of sedimentation has been frequently interrupted over circumscribed or wider regions—smaller or larger tracts of sea-bottom have again and again been elevated into dry land and subjected to denudation—so that it has been possible, without the aid of fossils, to ascertain the succession and relative age of the various groups of strata within certain limited areas. But when we come to compare the strata of such a region with the rocks of some other country, physical features alone will not enable us to decide whether the latter are of the same age or not as the strata of the region we have already examined. Strata, as we have seen, are continually varying in petrological character as they are followed along the strike—so that unless we have a continuous exposure or outcrop between two distant points we can never be quite sure that we are dealing with one and the same series. And this uncertainty becomes absolute when we attempt to correlate deposits occurring in widely separated regions of the earth's surface. It is just here where a knowledge of fossils becomes of supreme importance. Without their aid it would be impossible to construct any reliable geological chronology. By their means we are able to identify strata, no matter how much they may vary

in petrological character. They show us that a group of red sandstones and conglomerates here may be of approximately the same age as beds of limestone and shale occurring in some other place. Let us suppose, for example, that we have three conformable groups of strata,—A, B, and C,—A at the bottom, B in the middle, and C at the top, and each containing its own peculiar fossils. When we encounter in some other district any beds—no matter what their petrological character may be—charged with a series of fossils agreeing with those which we found in our oldest group A, we infer that the newly discovered strata are approximately of the same age as that group. In like manner we may detect by means of fossils the equivalents of the groups B and C. Again, we shall never find that the order in which the groups A, B, and C occur is reversed.[1] B will always occur above A, and C above B; C will never be met with underlying B, nor B underlying A. Should B not be present, then C will rest directly upon A. Thus by comparing and correlating fossiliferous strata we are able to assign to each set of beds its relative position; and geologists are thus gradually piecing together the fragmentary history of past ages.

Different Strata with same Fossils not necessarily quite Synchronous.—It does not follow, however, that strata occurring in widely separated regions, even although they contain the same groups of fossils, are necessarily contemporaneous. A little consideration will show us why this should be. Let us suppose certain physical or geographical changes to take place in the area of the Arctic Ocean, which compel the species at present living there to migrate southwards to the British seas; it is evident that the shells and other exuviæ lying in the marine silt of the far north will be of older date than those which are eventually buried in the sediment of their new habitat round our shores, even although the assemblage of species is precisely the same in both regions. It is obvious, therefore, that the appearance of the same set of fossils in widely separated regions may, and no doubt often does, point rather to the same kind of conditions having obtained, than to the actual synchronism of the deposits in which the fossils occur. Hence it has been proposed to apply the term *homotaxial* (*homotaxis*, similarity of order), to widely separated deposits which contain the same assemblages of fossils. By this term we would merely indicate that the "order of organic succession was the same at both places."

Gradual Extinction of Species.—A general glance at the fossils which occur in the various groups of strata shows us that

[1] The student must not, however, forget what has been said under the heads of "inversion" and "reversed faults." See pp. 183, 200.

those belonging to the uppermost, and therefore youngest, strata approach most nearly to the floras and faunas of the present day. And the farther down in the great series of fossiliferous strata we go, the farther we seem to recede from living forms—the fossil organic remains bringing before us types that depart more and more widely from those of existing species. Now, if we examine the fossils of two conformable groups of marine beds we may often notice that although each may have its peculiar set of fossils, yet there is no rapid and sudden change from the one set to the other. The species occurring towards the top of the upper group of beds may differ entirely from those met with towards the bottom of the lower group; but a larger or smaller number of species will be found to pass up from the lower group into the bottom beds of the upper group. In short, it is evident that the faunas and floras of the past did not all of a sudden die out, but became gradually extinct, and were just as gradually replaced by newer forms of life. There has been a continuous going out of old and coming in of new species.

Breaks in Succession.—Not infrequently the fossils of one set of beds are strongly marked off from those that occur in underlying strata. This will happen sometimes when we have beds of marine origin overlying fresh-water strata, or *vice versa*. Or we may occasionally come upon a seam of coal, composed of land-plants, resting directly upon a calcareous shale charged with remains of marine organisms. Such phenomena point, of course, to a change of physical conditions, and no long time need have elapsed between the formation of the separate beds. But we often encounter certain great and abrupt changes in the fossils of a series which cannot be so accounted for. Thus we may occasionally come across a series of apparently conformable marine strata containing totally discordant groups of fossils. The organic remains in the lower beds may differ wholly from those in the upper—it may be that not a single species or even genus is common to the upper and lower strata of the apparently conformable series. Now, such an abrupt change is a "break in the succession." A long period is necessarily implied by such a break. We have to allow time for the extinction of the older group of fossils, and for the gradual introduction of the totally divergent forms occurring in the upper beds. In such a case the geologist may reasonably suspect that the appearance of conformity is deceptive; and further investigation will probably disclose the fact that the upper set of beds rests upon an eroded surface of the lower. Thus, in true conformity we may expect to find a commingling of old and new forms at the line of junction, —for conformity points to the continuance of the same or nearly

similar geographical conditions; there is really no division-line between the two sets of beds, each line being often drawn merely for convenience of classification. In short, the lower beds pass up, as it were, gradually into the overlying series. Unconformity, on the other hand, indicates a more or less complete change of geographical conditions. There is a gap in the record—the lower-lying strata do not merge gradually into the overlying beds, but are sharply marked off from these. Hence at the junction between two such sets of strata we observe no intermingling of fossils—it may be that not a single species is common to the two groups.

Imperfections in the Geological Record.—A little reflection will serve to show that the fossiliferous strata cannot possibly contain a perfect record of all the forms of life which have successively tenanted our earth, for every bed of rock necessarily must have been formed out of the ruins of some pre-existing rocks—either igneous or derivative, or both. The younger strata are built up out of the ruins of the older. Thus many fossils which must at one time have existed have perished along with the strata in which they lay entombed. Again, we have no reason to suppose that the floras and faunas of the past were ever more fully represented by fossils than existing plants and animals will be by the remains which are now being washed into lakes and seas from the land, or which become buried where they live and die on the floor of the ocean. Who can believe that the organic remains which are at present being buried in fluviatile, lacustrine, and marine sediments, however abundant they may be, are completely representative of existing terrestrial and marine life-forms? Of the myriad species of terrestrial plants how few can be preserved as fossils—and so of terrestrial life generally, how feebly must our vertebrates and insects be exemplified by the few relics that find their way into lacustrine and estuarine sediments! Marine forms will of course be much more largely represented, but even amongst these there are numerous soft-bodied and delicately-fashioned creatures which can only be preserved as if by accident. And of many organisms, both terrestrial and marine, only the harder parts will remain, and these will be often incomplete, broken, and rolled. More than this, should the sea-bed be gradually upheaved, then each portion as it emerges will be attacked by the waves, denuded and reassorted. And still greater erosion of the sediments will be effected when the sub-aërial agents shall have worked over the newly-raised land for a prolonged period. Eventually a very large proportion of the upraised marine sediments, with their fossil contents, will be demolished, carried down to lower levels, and swept out to sea to form new accumulations. Now what we have been supposing would

happen in the event of a portion of the present sea-bottom becoming land, can be proved to have taken place again and again; so that the fossiliferous strata that enter so largely into the framework of our continents contain a very imperfect record of the past life-history of the globe.

Orderly Succession of Geological Changes.—The many blanks or gaps in the record were formerly believed to indicate that violent catastrophes had happened from time to time, by which life over the whole globe was suddenly extinguished, and such catastrophes were supposed to have been followed by a no less sudden introduction of entirely new forms. Subsequent research has dissipated those old views, and shown that, notwithstanding the many imperfections of the geological record, there is yet ample evidence to prove that gradual extinction of old and evolution of new faunas and floras has been the rule. As our knowledge of the earth's surface increases many gaps in the record are being filled up, while at the same time geologists are becoming more and more convinced that the imperfections which do exist are only a necessary result of the mode in which geological formations are amassed. It becomes increasingly evident that the present is merely a phase, as it were, of the past—that life has been persistent from its introduction, but subject all along to continuous modifications brought about by frequently recurring physical and climatic changes. There has been a continuity in geological history, and any subdivisions of past time that we choose to adopt must be arbitrary, for the germ, as it were, of one period must have begun in the period that preceded. So true is this that, as we shall see in the sequel, it is often hard to say, in the case of the better preserved portions of the stony record, where a so-called period ends and another begins. Our division-lines are not infrequently, like lines of latitude and longitude, drawn merely to enable us to fix relative geological positions—the lines themselves are often quite artificial.

Systems.—The forms of life that existed during some prolonged period of past time have a certain *facies* which serves to distinguish them as a group from the living things that flourished in preceding and succeeding ages. Now the strata which contain such a well-marked group or assemblage of fossils are included under the term of *system*. Thus a certain series of stratified rocks, which occur in Britain and the European Continent, in Greenland, in North America and elsewhere, is called the Silurian *system*, because it is characterised by fossils which have the same general *facies* or appearance. It is true that the species differ to some extent in the separate areas; but such differences we expect to

meet with, because individual species in our own time are for the most part restricted to provinces. Hence we must not feel surprised if in widely-separated contemporaneous or homotaxial strata we do not find quite the same assemblages of species. At present the climates of the various regions of the earth's surface are more strongly contrasted than they appear to have been at many epochs in the past; and as the limits of "provinces" are often determined by climatic conditions, it follows that existing species are usually restricted in their range. Some cosmopolitan ones there are, but these are exceptional, plants and animals being for the most part confined to certain provinces. But under the more equable climatic conditions which frequently prevailed during the past, individual species often spread themselves over vast areas. Thus some formations contain numerous cosmopolitan forms. In Carboniferous times, for example, many species of plants seem to have ranged over the whole world. This is not surprising when we know that at the period in question a genial and equable climate extended into polar regions. Under such conditions of climate it is not wonderful that the Carboniferous flora should have a well-marked *facies* in every region where its relics have been discovered. And so of many other systems laid down under singularly equable climatic conditions; their faunas and floras have a certain recognisable facies, numbers of the species being cosmopolitan.

Another distinguishing feature of a system is the abundant presence of certain orders or genera. Thus the Jurassic strata are characterised by the remains of remarkable types of sea-saurians. The Silurian system again everywhere contains more or less numerous representatives of the extinct order of Trilobites; and another equally characteristic Silurian form is the Graptolite. By the term *system*, then, is understood all the deposits, whether fresh-water or marine or terrestrial, which accumulated over the earth's surface in lakes, in seas, and upon the land, at a time when the world was characterised by the presence of some particular and peculiar fauna and flora.

The fossiliferous strata have, therefore, been subdivided into so many systems, the relative age of which has been determined by superposition, by the character of their included organic remains, and not infrequently by the circumstance that one set of strata often contains fragments of another; thus clearly showing that the former rocks are derivative from and, therefore, younger than the latter. By applying such tests to strata in many parts of the world geologists have been able to arrive at a chronological arrangement or classification, and so to construct a table showing the re-

lative positions which would be occupied by all the different groups of strata if these occurred together in one place. It must not be supposed, however, that these subdivisions are either of the same relative thickness, or that they represent periods of time of corresponding length. The geologist generally takes advantage of breaks in succession, unconformabilities and so forth, to draw his lines of demarcation; and thus his *systems* may differ to any extent in thickness and the length of time which they represent. In the absence of such physical interruptions he must be guided by fossils alone in forming his subdivisions. Systems defined by this means may be compared to such periods of human history as the "Middle Ages," the "Elizabethan Period," and so forth. It is evident that were there no gaps in the geological record the only subdivisions possible would be those based upon the characters of faunas and floras, and every boundary-line drawn would be artificial, however convenient and necessary for purposes of description.

Historical Geology.—The chronological arrangement of strata is of course only a means to an end. The geologist not only endeavours to ascertain the exact succession or relative age of strata, but he tries to trace out the horizontal extension of each group—noting all its peculiarities—with a view to discover the geographical and climatic conditions that obtained at the time of its accumulation. His object is to map out the relative position of land and sea as it varied during successive periods; to restore for us the various ancient floras and faunas that have clothed and peopled the earth in past times; to tell us all he can of former climatic changes; to indicate where and at what period volcanic action has manifested itself—in a word, to construct a history of the evolution of the earth's crust, and of the creatures which have lived and died upon its surface. For this purpose it is clear that physical and palæontological evidence must go hand in hand. To take cognizance of one alone and to neglect the other may lead to serious error. And in all our reasonings we must ever bear in mind that the wider the range of evidence we study, the more reliable our conclusions are likely to be. The results obtained by combining physical and palæontological evidence constitute what is termed *historical geology*.

Divisions of Strata.—The larger divisions and subdivisions of the fossiliferous formations are shown in the following table:—

IV. QUATERNARY or POST-TERTIARY.

Recent.

Pleistocene.

III. TERTIARY or CAINOZOIC.

- Pliocene.
- Miocene.
- Oligocene.
- Eocene.

II. SECONDARY or MESOZOIC.

- Cretaceous.
- Jurassic.
- Triassic.

I. PRIMARY or PALÆOZOIC.

- Permian.
- Carboniferous.
- Devonian and Old Red Sandstone.
- Silurian.
- Cambrian or Primordial.
- Archæan or Pre-Cambrian.

CHAPTER XXI.

HISTORICAL GEOLOGY—PRIMARY OR PALÆOZOIC SYSTEMS.

Archæan system—General character of the rocks—Cambrian system: life; physical conditions—Silurian system: life; physical conditions—Devonian and Old Red Sandstone system: life; physical conditions.

The sedimentary formations yield us no information as to the earliest portions of the earth's history. The geological record does not begin at the beginning: for any knowledge we may have of the opening chapters we are indebted to astronomers and physicists. According to them it seems probable that the earth formerly existed as a highly-heated nebulous mass, and that by and by it cooled and condensed and passed into the condition of a globe of molten matter; but in what particular manner it eventually acquired a solid crust we have probably yet to learn. Some are of opinion that solidification began at the surface, and that the interior is still in a liquid condition. Others maintain that any crust which at first formed at the surface would, owing to its greater density, sink at once and gravitate to the centre of the globe, and that this process would continue until the mass that still remained in a molten condition became too viscous or pasty to permit the descent of any more solidified material from the surface. Thus the superficial crust would maintain its position and continue to grow in thickness, until eventually all the underlying viscous or pasty matter stiffened, and the globe became solid throughout. Some physicists, however, think it probable that the stiffening process is not yet completed, and that between the crust and the solid nucleus there still exists a zone or stratum of unconsolidated or liquid matter. In the present state of our knowledge or ignorance we cannot conjecture which of these views may be nearest the truth. All we can say is that the geological phenomena are better explained on the hypothesis of a thin crust and a viscous or molten sub-stratum or nucleus, than on that of a practically solid globe, which, however, is the view that at present finds most favour with physicists.

The cooling globe having in some way acquired a crust, that crust, as cooling and contraction continued, would necessarily be folded and corrugated. And eventually, when the temperature at the surface had been so far reduced as to permit of the condensation of aqueous vapour, the seas would make their appearance. It is believed by many geologists that the great oceanic basins and continental areas were marked out at this early period ; but whether the primitive surface of any of those continental areas is now exposed to view is very doubtful. It is likewise doubtful whether any of the accumulations laid down in the earliest oceans and seas can now be recognised as such, or whether indeed any portion of them now remains open to our inspection. There are some good authorities, however, who incline to the opinion that the Archæan rocks, presently to be described, represent those earliest aqueous formations. If this be true, then the waters of the ocean at that time must have contained a considerably different proportion of ingredients than is now the case ; the formation of the rocks, as it is supposed, having been partly of the nature of chemical precipitations and partly of mechanical accumulations. Others, again, hold to the view that the Archæan schists, etc., are simply metamorphic rocks ; that some of them may formerly have existed as sedimentary fragmental strata, and others as eruptive igneous masses.

Thus it will be seen that the earlier history of the world is, like that of most nations, wrapt in obscurity, and will probably so remain for some time to come.

I.—ARCHÆAN or PRE-CAMBRIAN.

This system attains a thickness of many thousand feet, and consists principally of crystalline schistoze rocks, which are usually arranged in highly inclined and often extremely contorted strata. They are always the basement or oldest rocks in the regions where they occur, and there is invariably an unconformity between them and the strata which rest upon them. In some places, for example, they are overlaid unconformably by Cambrian. In many other regions, however, the strata which rest upon the crystalline schists are of later date than the Cambrian, and this being so it is obvious that we cannot assert that such crystalline schists are of the same age as those that underlie the Cambrian. All we can say with regard to them is that they are older than the strata above them. Under the term Archæan, therefore, it is possible that rocks of vastly different ages may be included. At

the same time the rocks described as Archæan have many features in common, and, until we know more about them, they may be conveniently grouped in one system.

Two groups are recognised in the Archæan system—the lower or "Old Gneiss formation," consisting principally of coarsely crystalline gneiss, with which are associated hornblende-schist, quartzite, and crystalline limestone. The upper group or "Crystalline-schist formation," is characterised by the prevalence of mica-schists, chlorite-schists, talc-schists, and phyllites, and now and again it contains conglomerates. Archæan rocks occur in many different parts of the globe. They are well developed in the Outer Hebrides and Ross and Sutherland (*Lewisian Gneiss*). Wide regions in Scandinavia, Finland, and the north-west of Russia, are occupied by them. They appear in the Urals, the Carpathians, and are well-developed in many of the hilly regions of Middle Europe (Saxony, Bohemia, and Bavaria). They are met with also in the Central Alps, the Taunus, the Pyrenees, the Sierra Nevada, etc. In America they extend over a vast area from the region of the great lakes north to the Arctic Circle, and they also form the nuclei of many mountain-ranges in the same continent. They occur in like manner in the coast-ranges of Brazil, in Venezuela, and the Andes. Archæan rocks have likewise been recognised in India and New Zealand.

The two groups composing the system are not always recognisable, but where this is well developed, as in Central Europe, they are sufficiently marked. In that region the lower seems to graduate up conformably into the overlying series. In Canada, however, there is a marked unconformity between the lower and the upper series. The former, termed *Laurentian*, attains a thickness of 30,000 feet, and is overlaid unconformably by the *Huronian*, comprising a series of strata of from 10,000 to 20,000 feet in thickness.

The *lower group* of the Archæan seems everywhere to be characterised by the prevalence of coarsely crystalline gneiss, which often passes into a massive rock that is not to be distinguished from granite. This granite-gneiss alternates in thick beds or lenticular masses with the ordinary gneiss, which is sometimes a micaceous, sometimes a hornblendic gneiss. Associated with this rock occur now and again layers and thicker masses of hornblende-rock, quartzite, dolomite, serpentine, crystalline limestone, magnetite, graphite, and in some regions hälleflinta. The gneissose rocks are further modified frequently by the presence of secondary minerals, such as garnets, various pyroxenes and amphiboles, epidote, apatite, zircon, tourmaline, etc. In one of the crystalline limestones of the

Laurentian in Canada occur the remains of what is believed by Sir W. Dawson, Dr. Carpenter, and others, to have been a massive reef-forming foraminifer. The masses or layers of this so-called *Eozoon* are usually built up of concentrically arranged alternate laminæ of white calcite and greenish serpentine, the calcareous layers being supposed to represent the original skeleton of the foraminifer, while the serpentine fills up the intervening chambers. But the organic origin of these remarkable masses of calcite and serpentine (ophicalcite) has been called in question by Messrs. King and Rowney, and more recently by Professor Möbius.

The *upper group* of the Archæan comprises a series of rocks which are upon the whole not so coarsely crystalline as those of the lower series. Mica-schist predominates in the lower portion of the group, and slates and phyllites in the upper. Interstratified with the prevalent mica-schist occur such rocks as hornblende-schist, chlorite-schist, talc-schist, quartzite, conglomerates, crystalline limestones, and fine grained gneisses. The overlying phyllite series is distinguished by the prevalence of slaty and fine-grained schistoze rocks, chief among which are phyllites. With these are associated quartzite, quartzose-schists, limestone, hornblende-schist, and some fine-grained gneisses.

In Scotland the Lewisian or "Fundamental" Gneiss is overlaid unconformably by thick masses of dull red and purple conglomerate and sandstone, known as the Torridon Sandstone. Only obscure traces of annelids occur.

The Archæan rocks are penetrated in many places by bosses and dykes, veins and other irregular intrusions of granite, syenite, diorite, etc. But whether these eruptions took place in Archæan times or later, can seldom be satisfactorily ascertained. But contemporaneous flows of gabbro, diabase, melaphyre, and quartz-porphyry are interbedded with the upper members of the Huronian in the Lake Superior region. Rhyolitic lavas and volcanic fragmental materials, are also associated here and there in Wales and England (as in the Malvern Hills, the Wrekin, etc.), with what are supposed by some geologists to be Archæan rocks.

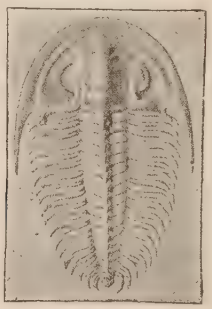
By those who deny the organic origin of Eozoon, the Archæan rocks are often termed *Azoic*, while those who believe it to be a true fossil prefer to call the same great series of rocks *Eozooic*. The alternations of bedding, and the appearance of conglomerates is certainly strongly suggestive of the original clastic condition of a large proportion of the Archæan strata, while the abundant scales, streaks, layers, and beds of graphite, may possibly represent metamorphosed vegetable matter. In like manner it is supposed that the great masses of iron-ore, so marked a feature

of the Laurentian, may owe their origin to the action of vegetable life.

II.—CAMBRIAN.[1]

This system is represented in Wales and Western England by a thickness of probably not less than 12,000 feet of coarse red and purple sandstones, grits, and conglomerates, and some greyish blue and green slates and slaty shales. It is doubtful whether the true base of these rocks is seen, so that their precise relation to the Archæan strata has not yet been satisfactorily made out. The

122. Lingulella ferruginea.



122*. Olenellus callavei.

123. Leperditia Cambrensis.

Figs. 122 to 123.—FOSSILS FROM THE LOWER CAMBRIAN.

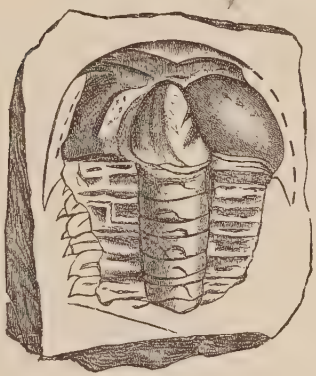
lower portions of the series, so far as known, are unfossiliferous, but in the higher lying strata Dr. Hicks detected organic remains. In S.E. Ireland the Cambrian reaches several thousand feet: the base of the system is not seen. The strata generally resemble those of Shropshire and North Wales. They have yielded worm-tracks and burrows and other markings, the most noteworthy fossil being *Oldhamia*. The English Cambrian rocks are arranged as follows:—

CAMBRIAN	UPPER	4 Tremadoc slates 3 Lingula Flags	= 12,000 feet or more.
	MIDDLE	2 Menevian	
	LOWER	1 Harlech and Llanberis	

Foreign Cambrian.—Cambrian strata probably extend underneath the younger formations of England to reappear in the Ardennes, the Thüringer Wald, and Bohemia. They occur also in

[1] Name given by Sedgwick to strata in North Wales, some of which, however, are now included in the Silurian system.

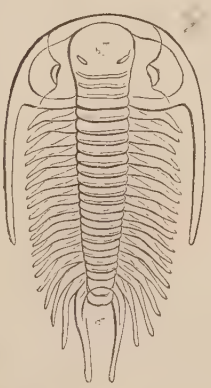
124. Protocystites Menevensis.



125. Paradoxides aurora.

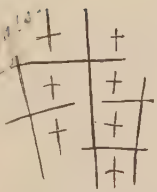
126. Arionellus longicephalus.

127. Theca antiqua.



130. Paradoxides Davidis.

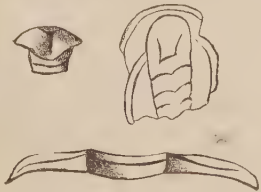
128. Microdiscus sculptus.



129. Protospongia fenestrata.

131. Agnostus Cambrensis.

132. Conocoryphe coronata.



133. Paradoxides Harknessii.

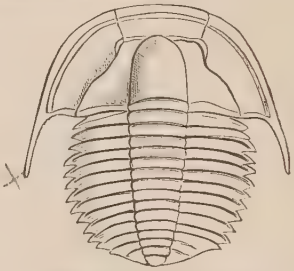
134. Discina pileolus.

Figs. 124 to 134.—FOSSILS FROM THE MENEVIAN GROUP.

Scandinavia and in Spain. In North America they comprise two groups, the Upper or Acadian and the lower or Potsdam, which are well developed in Newfoundland, Nova Scotia, New Brunswick, Massachusetts, Vermont, New York, and Canada. They also range along the Appalachians, and occur at many points in the Mississippi basin, and farther west in the slopes of the Rocky Mountains.

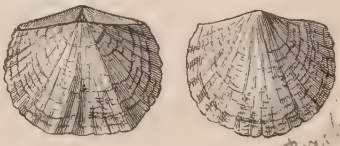
Life of the Period.—The life of the Cambrian, although meagrely represented, yet shows a remarkable variety of forms—there are no traces of terrestrial vegetation, the only relics of

135. Lingulella Davisi.



136. Conocoryphe bucephala.

137. Hymenocaris vermicauda.

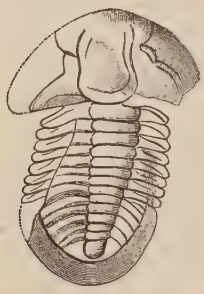


138. Orthis lenticularis.

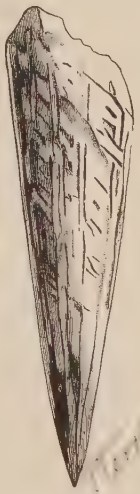
Figs. 135 to 138.—FOSSILS FROM THE LINGULA FLAGS.

plant-life being certain markings which are supposed to have been left by fucoids. The *Oldhamia* is of doubtful affinity, and may either be a plant or a zoophyte. The sponges are represented by such forms as *Protospongia* (fig. 129); the Echinodermata by sea-lilies (*Dendrocrinus*), cystideans (*Protocystites*, fig. 124), and star-fishes (*Palæasterina*). Annelid-burrows and worm-castings are often extremely abundant. Crustaceans are likewise numerous, being represented by ostracods (*Leperditia*, fig. 123); and phyllopods (*Hymenocaris*, fig. 137), but chiefly by the extinct group of the trilobites, of which some characteristic species are represented in figs. 122*, 125, 126, 128, 130, 131, 132, 133, 136, 139, 142, 144. These trilobites vary much in size, some of the dwarf forms (*Agnostus*), the fraction of an inch in size, being blind, while others (*Paradoxides*) had large eyes and attained a length sometimes of

two feet or more. Molluscoids are represented by brachiopods (*Lingulella*, *Discina*, *Orthis*, figs. 122, 134, 135, 138, 145), Mollusca by pteropods (*Theca*, *Conularia*, figs. 127, 140), heteropods (*Bellerophon*, fig. 141), lamellibranchs (*Palæarca*, fig. 143), and cephalopods (*Orthoceras*, *Cyrtoceras*). It is worthy of note that some Cambrian

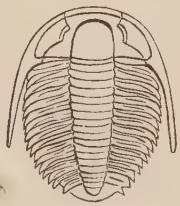


139. Asaphus Homfrayi.

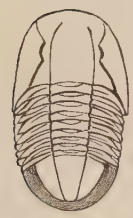


140. Conularia Homfrayi.

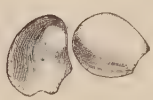
141. Bellerophon Arfonensis



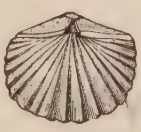
144. Angelina Sedgwicki.



142. Niobe Homfrayi.



143. Palæarca Hopkinsoni.



145. Orthis Carausi.

Figs. 139 to 145.—FOSSILS FROM THE TREMADOC SLATES.

forms have survived to the present, such as the genera *Lingula* and *Discina*.

Physical Conditions.—The enormous thickness attained by the Cambrian strata of Britain points to the existence at the time of some wide land-surface from which the sediment was derived. It is probable that this ancient land-surface lay chiefly to the north of the British area, but it seems to have included a considerable portion of what are now the Highlands of Scotland. According to Sir A. C. Ramsay, the Cambrian sandstones of Ross and Sutherland were deposited in a great inland sea

or lake. The equivalent strata of England and Ireland would appear to have been marine deposits, but it is possible that the unfossiliferous red and purple strata of those regions may, as Ramsay has suggested, be of lacustrine origin. His view is that the series began to be laid down in inland fresh waters, which, however, were subject to occasional invasions of the sea, probably owing to subsidence of the land. This he thinks would account for the alternation of fossiliferous and unfossiliferous strata. As the accumulation of the series continued, subsidence prevailed and the Anglo-Hibernian area eventually became wholly marine. The frequent appearance of false-bedding, of coarse-grained grits, of ripple-marks, sun-cracks, and rain-pittings, is forcibly suggestive of the shallow-water origin of a large proportion of the Cambrian sediments. Of the climatic conditions of the period we can say nothing.

III.—SILURIAN.[1]

The Silurian system of Britain is typically developed in Wales, and consists of two great series, *lower* and *upper*, the latter resting unconformably upon the former. The rocks consist principally of grits, slates, dark shales, flagstones, sandstones, and conglomerates, and interbedded with these occur occasional calcareous bands, and more or less lenticular beds of limestone. The succession of the various members of the system is given as follows :—

Upper Silurian	6. Ludlow Group . . .	2,000 feet
	5. Wenlock Group . . .	1,600 „
	4. Llandovery Group . . .	3,000 „
Lower Silurian (*Ordovician*)	3. Bala and Caradoc Group . .	6,000 „
	2. Llandeilo Group . . .	3,000 „
	1. Arenig Group . . .	4,000 „
	Approximate average thickness .	19,000 feet

The Lower Silurian strata of Wales pass down conformably into the uppermost beds of the Cambrian, and are widely distributed over a large part of the British Islands. Strata of the same age are exposed at the surface in many of our hilly districts. Thus they form the high grounds of Westmoreland and Cumberland, and the larger portion of the Southern Uplands of Scotland. The Highlands were formerly believed to be chiefly composed of Lower Silurian strata, but the recent work of the Geological Survey in the North-

[1] So called from an old British tribe, the Silures, who inhabited part of South Wales, where this system is well developed.

west Highlands now throws much doubt on this determination. Until the true horizon or stratigraphical position of the crystalline schists of the central Highlands has been ascertained they have been grouped together and termed *Dalradian*. Possibly they may represent several systems. In Ireland Lower Silurian rocks are likewise well developed in the mountainous tracts; nor can there be much doubt that the same strata, buried under younger systems, extend throughout the major portion of the British area.

The deposition of the Lower Silurian was marked by the development of considerable volcanic activity. Thus a great series of felsitic lavas and sheets of volcanic fragmental rocks accompany the Arenig group, and are well displayed in the mountains of Cader Idris, Aran Mowddwy, the Arenigs, and the Moelwyns. Again in the Bala and Caradoc group occur numerous beds and bands of similar volcanic rocks, which attain a great thickness in Snowdon and the surrounding area. Similarly lavas and tuffs form a large portion of the Lower Silurian of the Westmoreland hills, where they seem to represent part of the Bala and the whole of the Llandeilo groups of Wales. In the south-west of Scotland (Ayrshire) lavas and tuffs likewise make their appearance in the Lower Silurian, and the same is the case with the Lower Silurian in the south-east of Ireland.

The Upper Silurian strata of Wales and the west of England rest upon a denuded surface of the Lower Silurian—there is thus a distinct unconformity between the two series. The rocks of the upper series are arranged as follows :—

3. Ludlow Group	Tilestones, Downton Sandstones ; Ledbury Shales. Upper Ludlow Beds (with bone-beds). Aymestry Limestone. Lower Ludlow Beds.	
2. Wenlock Group	Wenlock or Dudley Limestone Wenlock Shale, Sandstone, and Flags Woolhope or Barr Limestone and Shale.	Denbighshire Grits, Shales, Slates, and Flags of North Wales.
1. Llandovery Group	Tarannon Shales ; Mayhill Sandstones.	

Foreign Silurian.—Silurian strata occupy wide tracts on the continent of Europe. In Norway they are developed chiefly in the neighbourhood of Christiania and the Mjösensee. Around Bergen the strata are highly metamorphosed. In the Christiania district, however, the strata although of inconsiderable thickness, yet contain a series of beds which seem to correspond to the chief groups of the English succession. Silurian strata likewise appear in the south of Sweden and some of the islands in the Baltic, but attain their

greatest development in Russia. From the islands of Dagöe and Œsel they extend eastwards through Esthonia and the north part of Livonia to the southern shores of Lake Ladoga. Throughout all that region they lie in approximately horizontal beds, consisting of sandstones, shales,—many of which are bituminous,—and argillaceous limestones, so that the strata closely resemble the undisturbed and less compacted rocks of much younger formations. They probably continue eastwards under the great drift-covered plains of Northern Russia, for they crop up again along the flanks of the Ural mountains, where they are inclined at high angles and partly metamorphosed. In Middle Europe, the Silurian occurs only in small isolated areas, as in Bohemia, where it has yielded a rich variety of organic remains, chiefly to the indefatigable researches of Barrande. Other localities where strata of the same age appear, are the Harz, the Thüringer Wald, the Fichtelgebirge, the Frankenwald, etc., but in none of those places are the strata so fossiliferous as in Bohemia ; they pass down conformably into the Cambrian. In the Eastern Alps a narrow belt of Silurian flanks the crystalline schists which form the central zone of the mountains. Silurian rocks are met with also in Belgium (Brabant), in France (Brittany and Normandy), and in Spain and Portugal. In North America they attain a vast development—extending westwards from the mouth of the St. Lawrence by the great lakes, through Wisconsin and Minnesota into the far North-West for an unknown distance, and south-west along the western slopes of the Alleghanies into Alabama. Other more or less isolated areas are met with in the interior of the continent, as between the Alleghanies and the Mississippi ; so that Silurian rocks, concealed under younger formations, probably extend throughout the interior continental basin. They re-appear in the Rocky Mountains and occur, with their typical fossils, in the islands of the Arctic Archipelago. They have been also recognised in the Cordilleras of South America, in the Himalaya, and in Australia.

Life of the Period.—Fossils often abound in Silurian rocks, more especially in the calcareous groups. Frequently, however, the strata appear to be somewhat unfossiliferous.

Plant-remains consist almost exclusively of certain more or less obscure markings which are believed to represent fucoids or seaweeds, and it has been suggested that the layers of anthracite which now and again occur in Silurian strata may owe their origin to great accumulations of such plants. Few traces of land-plants have been met with, and these indicate a cryptogamic flora. Seed-vessels or spore-cases of lycopodiaceous plants have been determined, in British Silurian; and in Bohemia, Germany, and North America

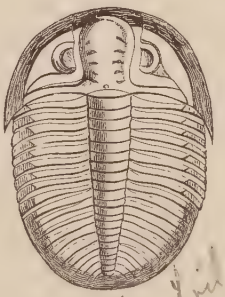
146. Orthis calligramma.

147. Trinucleus concentricus.

148. Strophomena rhomboidalis.

149. Murchisonia simplex.

152. Orthoceras mendax.



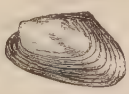
150. Ogygia Buchi.

151. Murchisonia subrotundata.

153. Acidaspis Jamesi.

154. Trochoceras cornu-arietes.

155. Euomphalus corndensis.



156. Modiolopsis expansa.

157. Palæarca amygdalus.

Figs. 146 to 157.—FOSSILS FROM THE LOWER SILURIAN.

rocks of similar age have yielded remains of the same group of plants—a rhizocarp (*Sphenophyllum*) also occurring in the Silurian of the last-named region.

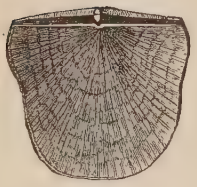
Amongst the lower forms of animal life are foraminifers (*Receptaculites*, etc.), sponges (*Amphispongia*, *Astylospongia*, *Ischadites*), and the enigmatical *Stromatopora*, which seems to have had affinities both with foraminifers and sponges. By others this form is referred to the Hydrocorallina, and is thought to have been related to the living *Millepora*. Radiolarians also occur.

Amongst the Cœlenterata were numerous forms of graptolites and corals. The former are eminently characteristic of the Silurian—some species being confined to the lower and some to the upper series. The graptolites with two rows of cells (diprionidian), are most numerously represented in the Lower Silurian; those with a single row of cells (monoprionidian) being most common in the Upper Silurian. Corals abounded—some of the limestones appearing to be almost wholly made up of their remains. Some common or characteristic rugose forms were *Omphyma* (fig. 169), *Zaphrentis*, *Petraia* (fig. 170), *Cyathophyllum* (fig. 166), *Arachnophyllum* (fig. 165), etc. Prominent tabulate forms were *Halysites*, *Chætetes*, *Favosites*, etc. The living Alcyonarian corals (*Heliopora*) were represented by *Heliolites*.

The Echinodermata were well represented by numerous crinoids or sea-lilies, such as *Cyathocrinus*, *Marsupiocrinus*, etc.—the jointed stems and arms of which largely compose some limestones. Less numerous are the remains of cystideans (*Echinosphærites*, *Pseudocrinites*, etc.), star-fishes, and brittle-stars (*Protaster*, fig. 160).

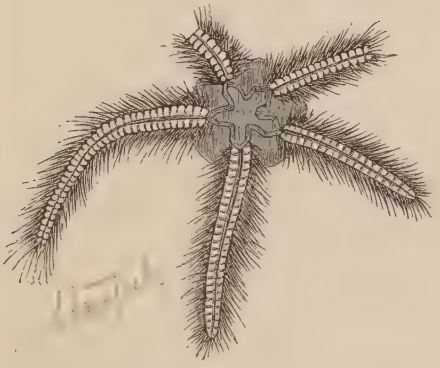
The tracks of annelids are often seen on the surfaces of beds, and the filled-up tubular burrows of sea-worms frequently occur. Jaws of annelids are sometimes found, and occasionally we get their tubular cases (*Serpulites*, *Spirorbis*) attached to shells, corals, etc.

The crustacean remains include some of the most characteristic Silurian fossils. Foremost among these is the extinct family of trilobites, which made its first appearance in the Cambrian and lived on into Devonian and Carboniferous times, but attained its greatest development in the Silurian period. There are many genera and species of these remarkable crustaceans, and almost every subdivision of the strata has its own characteristic forms, but the family culminated in the Lower Silurian age. Some widely distributed forms are *Ogygia* (fig. 150), *Trinucleus* (fig. 147), *Acidaspis* (fig. 153), *Illænus* (fig. 163), *Calymene* (fig. 162), *Phacops* (fig. 164), etc. Other remarkable crustaceans were the eurypterids (an extinct order most nearly allied to the existing king-crabs), which appear for the first time in the Ludlow rocks. One of these (*Pterygotus*



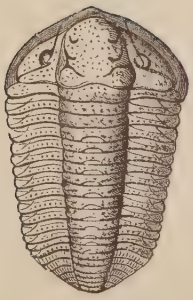
158. Strophomena euglypha.

159. Pentamerus oblongus.



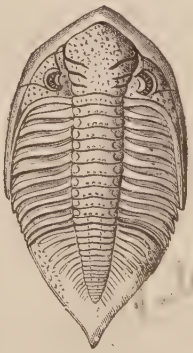
160. Protaster Miltoni.

161. Trematonotus dilatatus.



162. Calymene Blumenbachi.

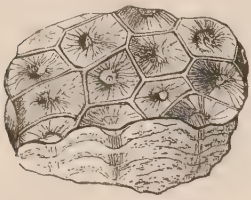
163. Illænus Barriensis.



164. Phacops caudatus.

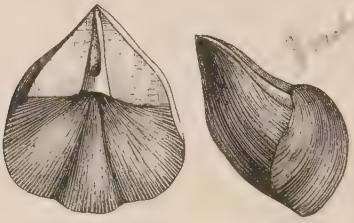
Figs. 158 to 164.—FOSSILS FROM THE UPPER SILURIAN.

punctatus) was seven or eight feet in length. Ostracods (*Beyrichia*) and phyllopods (*Ceratiocaris*) also occur in Silurian rocks. The



165 Arachnophyllum typus.

166. Cyathophyllum truncatum.



167. Cyrtia exporrecta.

168. Rhynchonella navicula

169. Omphyma turbinata.

170. Petraia bina.

171. Orthoceras annulatum.

Figs. 165 to 171.—FOSSILS FROM THE UPPER SILURIAN.

first scorpion (*Palæophoneus*) and first insect (*Palæoblattina*, a form of cockroach) have likewise been recorded from this system.

Various lace-corals (*Fenestella*) and other Polyzoa occur, but by far the most abundant forms amongst the Molluscoida were the brachiopods. Characteristic types are *Orthis* (fig. 146), *Strophomena* (fig. 158), *Leptæna*, *Pentamerus* (fig. 159), *Cyrtia* (fig. 167), and *Rhynchonella* (fig. 168). Lamellibranchs were much less numerous —characteristic forms being *Modiolopsis* (fig. 156), and *Palæarca* (fig. 157). Amongst gasteropods the more common genera are *Pleurotomaria*, *Murchisonia* (figs. 149, 151), *Euomphalus* (fig. 155), *Trematonotus* (fig. 161), etc. The cephalopods are well represented by straight and coiled chambered shells; amongst the former is the genus *Orthoceras* (figs. 152, 171), some forms of which reached a length of six feet and more; the latter show such types as *Trochoceras* (fig. 154), *Phragmoceras*, *Cyrtoceras*, *Nautilus*, etc.

Vertebrates make their first appearance in the Ludlow rocks. The remains consist of bony bucklers or head-shields of ganoid fishes (*Pteraspis*, *Cephalaspis*), the defensive spines of some cestraciont (*Onchus*), and fragments of shagreen-like skin and plates which may have belonged to placoid fishes.

Physical Conditions.—The Silurian system is eminently marine, and its wide distribution shows that during its accumulation vast tracts of the present continents were overflowed by the sea. None of the deposits, however, indicates true oceanic conditions. The strata for the most part appear to have been laid down in shallow seas, which here and there may have been moderately deep. During the formation of the Lower Silurian the whole area of the British Islands, with the exception, perhaps, of some of the Archæan tracts of the north-west, appears to have been under water. The submergence had commenced in Cambrian times and was continued up to the close of the Lower Silurian period. During this period of submergence volcanic activity manifested itself as we have seen at various points. According to Sir A. C. Ramsay our terrestrial scenery consisted in Lower Silurian times of groups of volcanic islands scattered over the area of what is now North Wales and South Wales, and extending westward into the Irish region and northward into the Cumberland district and the south of Ayrshire.

A marked unconformity separates the Upper from the Lower Silurian in many places in Britain. The lower series had been upheaved and considerable tracts of the Lower Silurian sea had been converted into dry land, and its sediments had suffered some contortion and considerable erosion before the deposition of the Upper Silurian commenced. According to Ramsay it would appear that at the beginning of Upper Silurian times part of what is now Wales consisted of islands formed of Lower Silurian rocks, round

the shores of which the basement-beds (Upper Llandovery) of the upper series were accumulated as beach-deposits. Ere long submergence again set in—the beach-beds of the Upper Llandovery being deposited at higher and higher levels of the sinking land-surface, until at last this disappeared and eventually became buried under the succeeding strata of the Upper Silurian. Ramsay has referred to one of these old Silurian islets (Longmynd and Shelve Hills) of which he gives the accompanying section (fig. 172). The marginal deposits (4) of the Upper Silurian are seen lying along the base of the hills, and occurring also as an *outlier* on the flat hill-top. The succeeding strata (5) no doubt originally extended over these hills, their absence being due to denudation. Thus then we have evidence of the former existence of an island which at the beginning of Upper Silurian times was about the size of the Isle of Man. Gradually it subsided, until by and by if was overwhelmed in the sea.

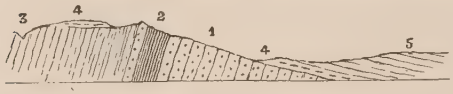


Fig. 172.—1, Lower Cambrian; 2, Lingula Flags; 3, Tremadoc and Arenig beds; 4, Llandovery beds; 5, Wenlock. (R.)

From what particular land-areas the sediments of the Lower Silurian were derived we cannot tell. But the enormous thickness attained by the strata points to long-continued and powerful erosion of some land-surface, which in all probability consisted chiefly of Archæan rocks, and perhaps in part of Cambrian strata. The occurrence of thick conglomerates of old crystalline rocks in Carrick is strongly suggestive of the existence of some land formed of Archæan rocks which may have existed in the north-west. The Upper Silurian sediments seem to have been largely derived from the denudation of Lower Silurian and Cambrian, and probably in part also of Archæan areas. It is most probable, indeed, that the chief land-masses during Silurian times were grouped in the north-west of the European area—and that they were composed essentially of Archæan rocks. In like manner the oldest land-surfaces of the North-American continent lay towards the north. But probably the great continental ridges rose to the surface here and there in other regions, so as to form groups of islands, as in Bavaria and Bohemia.

The temperature of the Silurian seas appears to have been remarkably equable, so as to have allowed of the migration of the same or closely allied species of molluscs, crustaceans, etc., over vast regions. In the Arctic regions fossils occur which are identical with English Silurian forms, but the general facies of the Arctic Silurian fauna is rather American than European. All the fossils

referred to belong, of course, to extinct species, but the fact that they consist largely of corals and cephalopods seems to bespeak genial climatic conditions. And the further consideration that the same or very similar species occur in Silurian strata in low latitudes of the temperate region is strong proof that the Arctic seas of Silurian times were genial. It is to be noted, however, that in the Lower Silurian of Scotland blocks of gneiss and other crystalline rocks attain such a size that it is difficult to see how they could have been transported without the agency of floating ice. Some of these blocks are five, six, and even nine feet in diameter. Similar boulder-beds occur in the Lower Silurian of the Lake Superior region. It is possible, therefore, that glaciers may have descended here and there to the sea-level during Lower Silurian times.

IV.—DEVONIAN AND OLD RED SANDSTONE.

Devonian.—These strata are divided in Devon and Cornwall into lower, middle, and upper groups. The base of the lower group is not seen, so that we do not know what relation it bears to the Silurian. The upper group passes conformably into the Lower Carboniferous system. Probably the whole thickness of the English Devonian does not exceed 10,000 or 12,000 feet. The general character of the rocks is as follows :—

Upper Group.—Calcareous grey and brown slates, passing down into brown and yellow sandstones that overlie hard grey and reddish sandstones and flagstones.

Middle Group.—Unfossiliferous slates, passing down into calcareous fossiliferous slates with intercalated limestones, which rest upon hard green, red, and purplish sandstones, grits, and conglomerates.

Lower Group.—Soft slates with calcareous layers and some sandstones, resting on schists and reddish sandstones.

Old Red Sandstone.—In Wales, Scotland, and Ireland we meet with no strata exactly corresponding to those just described. But occupying precisely the same stratigraphical position or horizon there appear thick deposits of red sandstones and conglomerates, which form what is called the Old Red Sandstone series. In Wales these beds appear to pass down conformably into the Upper Silurian, and to graduate upwards into the Carboniferous system. The Old Red Sandstone of Scotland comprises two groups of strata —the upper resting unconformably on the lower. The two groups contain the following series of strata :—

Upper Group : a great series of red sandstones, clays, conglomerates, and breccias—the sandstone in some areas being yellow, grey, or white. The conglomerates and breccias occur chiefly

along the marginal areas of the formation, as in the Lammermuirs and the Cheviots. The strata are usually unfossiliferous, but remains of ganoid fishes occasionally occur, such as *Pterichthys major* and *Holoptychius nobilissimus*. The series passes up conformably into the Lower Carboniferous, as in Orkney, the Moray Firth district, and the Borders of Scotland and England.

Lower Group: a thick series (20,000 feet as a maximum) of coarse grey, red, brown, and purplish, and sometimes yellow sandstones, grey flagstones, clays and shales, coarse conglomerates, and local lenticular beds of limestone and cornstone. Associated with these strata are interbedded lavas (porphyrite, diabase, etc.) and tuffs, which, in some regions (Sidlaws, Ochils, Pentlands, Cheviots, Ayrshire, etc.) attain a thickness of several thousand feet. The fossils consist of fishes and crustaceans, and badly preserved plants, which are chiefly lycopodiaceous. In Lanarkshire a thin band of shale in the group has yielded a graptolite and two Upper Silurian forms—*Spirorbis Lewisii* and *Orthoceras dimidiatum*.

In Ireland Old Red Sandstone, containing some plant- and fish-remains, a few crustaceans, and the earliest fresh-water bivalve (*Anodonta Jukesii*, fig. 174), passes conformably upwards into the Carboniferous, and overlies unconformably the "Glengariff grits," which pass down conformably into the Upper Silurian, and are probably the equivalents of the Lower Old Red Sandstone of Scotland.

In Wales the Old Red Sandstone lies along the south and south-eastern borders of the Silurian rocks, covering the wide area watered by the Usk and the Wye. It extends south-west underneath the South Welsh Coalfield into the Bristol Channel. The Scottish strata are developed chiefly in the Lowlands, where they flank the Silurian strata of the Highlands and the Southern Uplands—and are probably continuous underneath the overlying Carboniferous strata over the whole breadth of Central Scotland. Other wide areas occur in the lower basin of the Tweed, along the borders of the Moray Firth, in Caithness, Orkney Islands, etc. In Ireland Old Red Sandstone strata are developed chiefly in the west and south-west.

Foreign Devonian and Old Red Sandstone.—It is known from artificial borings that Devonian strata occur under overlying later formations in the south of England. These probably extend southwards and become continuous with strata of the same age which rise to the surface in the north of France. In like manner, the large tract of Devonian rocks that extends from the Boulonnais eastwards through Belgium to Westphalia probably has a very much wider extension underneath the younger formations of Central Europe. In Northern Russia the Devonian strata, like those of

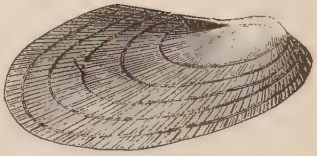
Silurian age, occur in horizontal beds which cover an area of 7000 square miles ; but the area concealed under younger deposits is probably very much greater, for Devonian strata appear ridged up along the flanks of the Urals. From this it may be inferred that they extend across the whole breadth of Russia. The Russian strata are remarkable for showing alternations of calcareous and arenaceous rocks—the former of which contain an assemblage of fossils of a distinctly Devonian facies, while the latter are charged with the remains of a fish-fauna resembling that of the Scottish Old Red Sandstone. In Central Europe the Devonian strata have much the same general appearance as those of England, the middle group being the most fossiliferous. In many places in Germany the Devonian strata contain intercalated beds and sheets of basalt-rocks (diabase), and volcanic breccias and tuffs. Metalliferous veins also traverse the strata in some places both in Germany and England. In North America the Devonian system is composed partly of marine strata which are comparable to the similar strata of the system in Europe, and partly of a series of red and yellow sandstones, conglomerates, etc., containing many land-plants and some fish-remains, but very few traces of a marine fauna. This arenaceous series occurs in Nova Scotia and New Brunswick. The marine or Devonian type has a much wider range, being largely developed in the Mississippi basin, and occurring also in the Appalachian region and the State of New York.

Life of the Period.—Besides fucoidal markings, which are common in the Devonian or marine strata, a considerable number of land-plants are met with in the Old Red Sandstone series of rocks —more especially in those of Nova Scotia and New Brunswick. Among these were tree-ferns, such as *Caulopteris*, and the smaller forms of fern—*Cyclopteris* (fig. 173), *Archæopteris*, *Sphenopteris*, *Neuropteris*, etc., also great club-moss trees (Lepidodendroids), gigantic horsetails (*Calamites*), and huge Sigillarioids. One of the most characteristic plants is *Psilophyton*, which seems to have had affinities with lycopods and rhizocarps. Besides these there were also large coniferous trees, such as *Dadoxylon ;* and *Cordaites*, probably allied to conifers and cycads.

The lower forms of animal life are represented most characteristically by such forms as *Receptaculites* and *Stromatopora*, both of which attained a large size and greatly abounded. Among the cœlenterates were numerous forms of rugose and tabulate corals. Of the former, the most commonly occurring genera are *Cyathophyllum*, *Cystiphyllum*, *Calceola* (fig. 181), etc. The honeycomb corals (*Favosites*, fig. 183) are the most common of the tabulate forms. A well-known alcyonarian coral is *Heliolites* (fig. 182).

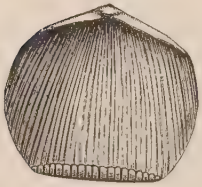
174. Anodonta Jukesi.

173. Cyclopteris Hibernicus.



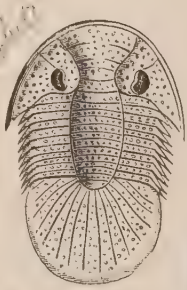
175. Pterinea dumnoniensis.

176. Murchisonia angulata.

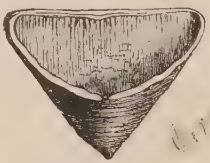


177. Rhynchonella cuboides.

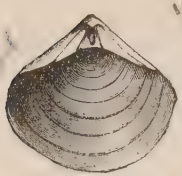
178. Spirifera Verneuili.



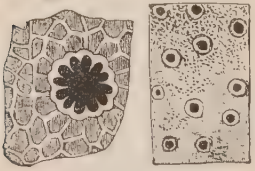
180. Bronteus flabellifer.



181. Calceola sandalina.



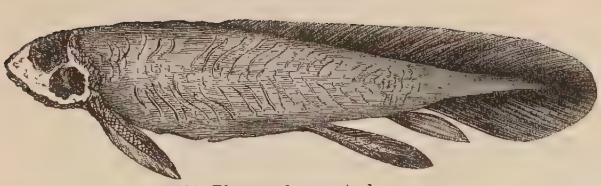
179. Stringocephalus Burtini.



182. Heliolites porosus.

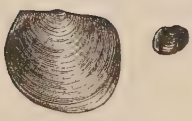
183. Favosites cervicornis.

Figs. 173 and 174.—FOSSILS FROM THE OLD RED SANDSTONE; Figs. 175 to 183 FROM THE DEVONIAN.

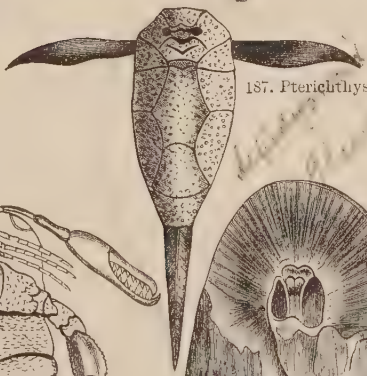


184. Phaneropleuron Andersoni.

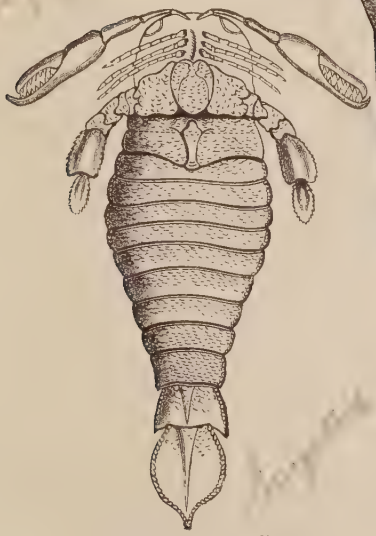
185. Holoptychius nobilissimus.



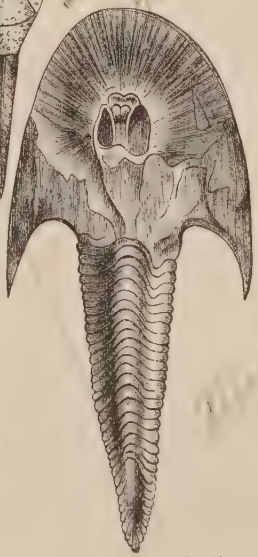
186. Estheria membranacea.



187. Pterichthys Milleri.



188. Pterygotus anglicus.



189. Cephalaspis Lyelli.

Figs. 184 to 189.—FOSSILS FROM THE OLD RED SANDSTONE

Echinoderms swarmed in the Devonian seas, the most plentiful forms being Crinoids (*Cupressocrinus* and *Cyathocrinus*). Cystideans, which died out in the Silurian, were now succeeded by the allied group of Blastoidea (*Pentremites*). Star-fishes and sea-urchins occur, but they all belong to Upper Silurian types.

Annelids are abundantly represented by tube-forming species (*Spirorbis*), and crustaceans by trilobites and eurypterids. The trilobites show no new types, but the species are distinct—the more notable genera being *Bronteus* (fig. 180), *Phacops*, and *Homalonotus*. Some of the eurypterids of the Old Red Sandstone (*Pterygotus*, fig. 188) were probably five or six feet long. The cypridina-slates of Germany are so called from the vast numbers of small ostracods (*Entomis*) which they contain. Phyllopods also occur, such as *Estheria* (fig. 186); and isopods (*Prœarcturus*), and long-tailed decapods (*Palœopalæmon*) make their first appearance.

From the Devonian of North America have come the remains of insects—one of which (*Platephemera*) had a spread of wing of five inches. The remains consist principally of neuropterous wings. Myriapods have also been recently recognised.

The Polyzoa continue to be well represented, chiefly by the lace-corals (*Fenestella*, *Retepora*), while brachiopods are very abundant. Very characteristic forms are the broad-winged spirifer (fig. 178), also *Uncites*, *Stringocephalus* (fig. 179) and *Rensselœria*, which are exclusively Devonian. Other families were the Rhynchonellidæ (*Rhynchonella*, fig. 177) and the Productidæ—the latter represented by the genera *Chonetes* and *Productella*. Among the lamellibranchs some of the more notable genera are *Pterinea*, *Megalodon*, *Cucullœa*, *Cardiola*, *Lucina*, etc., while the more important forms among the gasteropods are *Murchisonia* (fig. 176), *Euomphalus*, *Pleurotomaria*, *Bellerophon*, etc., and the earliest pulmonates (*Strophites*, etc.) The straight *Orthoceras* and other old genera (*Cyrtoceras*, etc.) of cephalopods are still present, but spirally coiled forms now begin to predominate, especially the genera *Clymenia* and *Goniatites*.

From the Old Red Sandstone chiefly come the remains of numerous fish—all of them ganoids, a group feebly represented in existing waters. Among these are the placoganoids, *Cephalaspis* (fig. 189), *Pterichthys* (fig. 187), *Coccosteus*, etc., and the lepidoganoids, *Holoptychius* (fig. 185), *Acanthodes*, *Osteolepis*, *Diplopterus*, etc. These and many others swarmed in the waters where the Old Red Sandstone was deposited. In Devonian strata they are of rarer occurrence. The largest placoganoid was the *Dinichthys* of North America—the armoured head of which was three feet in length. Other forms, such as *Dipterus*, and possibly *Phaneropleuron* (fig. 184), seem to be referable to the Dipnoi. The Elasmobranchii are also well represented.

Physical Conditions.—In the Devonian and Old Red Sandstone strata we see two distinct types of sedimentation, which are so strongly contrasted that we cannot doubt they point to different physical conditions. The former are unquestionably of marine origin, while the latter, according to Godwin-Austen and Ramsay, have been deposited in large lakes or inland seas. The geographical distribution of the Devonian in Europe, and the relation of that system to the Silurian, show that the Devonian sea did not cover so wide an expanse as that of the Upper Silurian. The sea had shallowed and the area of dry land had increased when the Devonian strata began to accumulate. We may picture to ourselves a time when the Atlantic extended eastwards over the south of England and the north-east of France, and occupied the major portion of Central Europe, sweeping north-east through Russia, and how much farther we cannot tell. North of that area stretched a wide land-surface, in the hollows of which lay great lakes and inland seas, which seem now and again to have had communication with the open ocean. It was in these lakes or inland sheets of water that the Old Red Sandstone strata were accumulated, while the Devonian or marine rocks were deposited in the sea lying to the south. Volcanic action manifested itself now and again within this latter area, for, as we have seen, ancient lavas and tuffs occur interbedded with the Devonian aqueous rocks in Germany. On a larger scale, however, were the volcanoes of Scotland. These seem to have been at first sub-aqueous—they broke out on the beds of the inland seas. But many of them poured out so much material that they eventually became sub-aërial. Such appears to have been the case with the old volcanoes of the Sidlaw Hills and the Cheviots. The Lower Old Red Sandstone period was brought to a close by considerable earth-movements—wide areas of the inland seas becoming converted into dry land, and subjected to powerful and long-continued erosion. Eventually, however, the land again became depressed, and the inland seas and lakes increased in extent, but did not apparently attain the dimensions reached by them in Lower Old Red Sandstone times. It was in these reduced inland seas that the Upper Old Red Sandstone was deposited.

The Old Red Sandstone is the record of a very prolonged period. When the lower beds began to be laid down an Upper Silurian fauna lived in the outlying ocean, and during some minor oscillation of level some stragglers from that fauna found their way into one of the ancient Scottish lakes. But before the close of the Old Red Sandstone period the Silurian fauna had vanished from the adjacent sea, and its place had been taken by Carboniferous forms.

The general facies and geographical distribution of the life of Devonian and Old Red Sandstone times is suggestive of genial climatic conditions. The numerous crinoids, corals, etc., could hardly have flourished in cold seas, and the occurrence of Devonian species within the Arctic Circle shows that the temperature of the ocean must have been much more equable than is at present the case. Many of the conglomerates, however, which occur in the Old Red Sandstone strata can hardly owe their origin to water-action alone. They have often quite the aspect of morainic accumulations—the stones being blunted, sub-angular, and smoothed, and even occasionally showing striated faces. Moreover, they are usually rudely huddled together in a dull tough arenaceous matrix. Deposits of this character cover considerable areas in Scotland, as in the Lammermuir Hills, where they are very apt to be mistaken for ordinary boulder-clay or till. Again, the frequent occurrence of isolated stones—waterworn and angular—scattered through the sandstones, etc., of the ancient lacustrine areas seems to indicate the action of ice which floated these out from the beaches. Many stones, however, might have been carried out from shore entangled in the roots of plants.

CHAPTER XXII.

HISTORICAL GEOLOGY — PRIMARY OR PALÆOZOIC SYSTEMS — *continued.*

Carboniferous system: life; physical conditions—Permian system: life; physical conditions—General character of Palæozoic faunas and floras—Evolution of Continental areas in Palæozoic times.

V.—CARBONIFEROUS.

The Carboniferous system is well-developed in the British Islands. It covers wide areas in Wales and the midland and northern counties of England. In Scotland, again, it extends over a great portion of the Lowlands which stretch across the country from sea to sea between the Highlands and the Southern Uplands; while in Ireland Carboniferous rocks occupy the central and by much the larger part of the island. The system shows the following succession of groups which are more or less persistent over the British area, but differ much in character in the various districts:—

3. Coal-Measures (2000 to 12,000 ft.)	Red Sandstone and Upper coal-bearing series. Middle coal-bearing series. Lower coal-bearing series (Ganister beds).
2. Millstone Grit (50 to 5500 ft.)	
1. Carboniferous Limestone (700 to 7000 ft.)	Yoredale beds. Main or Scaur limestone. Lower Limestone Shale (England), and Calciferous Sandstones (Scotland).

1. Carboniferous Limestone Series.—In South Wales and the adjacent districts in England the Carboniferous rocks rest conformably upon the Upper Old Red Sandstone. The basement beds (Lower Limestone Shale) consist of dark earthy shales, containing thin flaggy limestones in the upper portion of the series, and

resting upon a set of grey, yellow, green, and reddish sandstones, grits, clays, and shales, which form the passage-beds down into the Old Red Sandstone. The basement beds are succeeded in the same districts by a thick massive grey or bluish limestone (Mountain Limestone) which is one of the most characteristic members of the Carboniferous system and has been traced over a very extensive area. It is eminently of marine origin and is usually crowded with the débris of crinoids, corals, molluscs, etc., but in places the rock appears structureless, the fossils being then visible only when thin sections are examined under the microscope. Followed from South Wales (where it attains a thickness of 500 feet) in a northerly direction, the limestone gradually swells out, until in Central England it attains a thickness of 3000 feet. In that region (the Pennine chain) the limestone is overlaid by a series of sandstones, shales, limestones, and occasional coals, which varies in thickness from 500 to 4500 feet. As the limestone is traced into Scotland it begins to lose its massive character and becomes more and more split up or divided with intercalated beds of sandstone and shale and occasional coals and ironstones, until eventually the limestone-seams come to form a very inconsiderable part of the group.

In Scotland the lower part of the Carboniferous system contains two well-marked series—the Calciferous Sandstones and the Carboniferous Limestone—which may be looked upon as the equivalents of the Carboniferous Limestone series of England. The Calciferous Sandstones consist of an underlying group of red, brown, and sometimes yellow and white sandstones with intercalated red, green, and grey shales and clays, and an upper group of grey, yellow, and white sandstones, grey and dark blue and black shales and clays, with sometimes numerous thin seams of fine-grained argillaceous limestone (cement-stones), occasional beds of ordinary limestone, and seams of coal. The Lower or Red Sandstone group passes down conformably into the Upper Old Red Sandstone. The Upper or Cement-stone group of the basin of the Forth is noted for its bituminous shales, and for one of its limestones (Burdiehouse), from which the remains of a large number of fishes and other fossils have been obtained. The Scottish Carboniferous Limestone series is divisible into three groups—an upper group containing three or more beds of limestone (marine) interstratified with beds of sandstone and shale and occasional coal-seams ; a middle group of shales and sandstones, with numerous seams of ironstone and coal ; and a lower group of sandstones and shales, with three or more beds of limestone and occasional seams of coal and ironstone. These limestones vary in thickness from a foot or less up to 100 feet, and the

whole Carboniferous Limestone series does not exceed 2700 feet as a maximum thickness.

In Ireland the Carboniferous Limestone series is well developed. The lower portion of the series (Carboniferous Slate) attains a thickness of 5000 feet in the county of Cork, but this rapidly thins away northwards, so that at Kenmare the massive Carboniferous Limestone comes to rest directly on the Old Red Sandstone. This limestone reaches a thickness of 2500 feet in Central Ireland, and passes northwards into a series of shales, sandstones, etc., which recall in their aspect the Lower Carboniferous strata of Scotland.

Contemporaneous volcanic rocks are associated in Derbyshire with the Carboniferous Limestone, but it is in Scotland where we meet with the most abundant remains of Carboniferous volcanoes. The lavas and tuffs of the Calciferous Sandstone group attain a great thickness, and form some of the most conspicuous belts of hilly ground in the Lowlands. In Ayrshire and the west and south-west of Lanarkshire they occupy the place of the larger part of the Red Sandstone group. In the overlying Cement-stone group contemporaneous lavas and tuffs are likewise commonly met with, particularly in the basin of the Forth, but they form upon the whole less continuous sheets and masses, for they are the product of more or less sporadic and isolated volcanoes. Volcanic action in Scotland continued into the Carboniferous Limestone period and then died out. In Ireland, as in England, sheets of lava-form rocks and tuff occur interstratified with the massive Carboniferous Limestone.

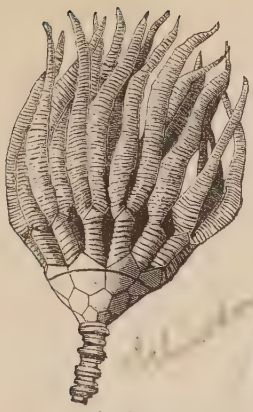
2. Millstone Grit.—The Mountain Limestone is overlaid in England by a series of sandstones and grits and subordinate beds of shale and clay which varies in thickness from 300 or 400 feet to 4000 or 5000 feet. Passing northwards into Scotland this series of rocks dwindles down from 400 feet to a few yards. In the Scottish series, which varies in thickness from 50 feet up to 900 feet, thick fireclays occur, and one or two lenticular seams of limestone.

3. Coal-measures.—Overlying the Millstone Grit comes a variable thickness of sandstones (chiefly white and yellow), dark grey and black shales, clay-ironstones, blackband-ironstones, fireclays, and coals. In South Wales the series reaches 12,000 feet in thickness, in Lancashire it is not so thick (6000 to 8000 feet), while in Scotland it does not exceed 2100 feet. In Lancashire the upper part of the series contains a set of red sandstones which is present also in the Scottish area, where it rests with a gentle unconformity upon the true coal-bearing strata. These red sandstones in Scotland attain a thickness of 900 feet in some places.

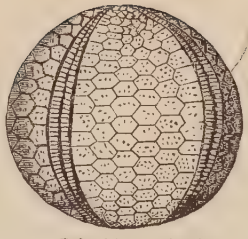
Foreign Carboniferous.—Carboniferous strata occur in the north of France and Belgium in more or less continuous areas, while small outlying basins of the same strata are dotted over Central and Southern France, and they are met with also in the north of Spain and Portugal. Similar detached areas occur likewise in Germany, as in Rhenish Prussia, Westphalia, Saxony, Silesia, and Bohemia. In Russia strata of the same age probably extend over a vast area between Moscow and the White Sea, but they are buried for the most part under younger formations. Carboniferous rocks appear in the Alps, in Tuscany, and in Sardinia. They have been noted also in Bear Island, in Nova Zembla, and in Spitzbergen. In Central Asia they occur in the Altai and in the valley of the Amur, and they have a wide development in the provinces of Shansi and Shantung in China. In New South Wales they are likewise well developed. But it is in North America where the system covers the widest area. Dana gives the extent of the coal-bearing area of that continent as follows :—

Rhode Island area	500	square miles.
Alleghany area	59,000	„
Michigan area	6,700	„
Illinois, Indiana, West Kentucky	47,000	„
Missouri, Iowa, Kansas, Arkansas, Texas	78,000	„
Nova Scotia and New Brunswick	18,000	„

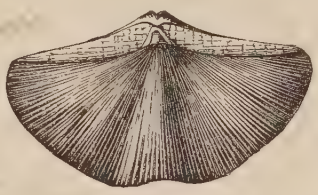
Life of the Period.—As might have been expected plants are very abundantly represented, and these are chiefly terrestrial. They belong almost exclusively to the flowerless or cryptogamic division, the most notable forms consisting of ferns, Equisetaceæ, and Lycopodiaceæ. Besides these were conifers, and the remarkable *Sigillariæ*. Ferns are extremely abundant, and comprise both herbaceous and arborescent forms, the former apparently greatly predominating. Amongst tree-ferns the commoner genera are *Caulopteris* and *Palæopteris*. The herbaceous forms are very numerous, such genera as *Neuropteris* (fig. 206), *Alethopteris* (fig. 204), and *Sphenopteris*, occurring abundantly, and having a world-wide distribution. The Equisetaceæ are represented by *Calamites* (figs. 205, 208), a kind of gigantic horse-tails. The stems of these plants were tall and cylindrical, those with a thin bark usually showing longitudinal ribs and transverse joints; while those with a thick bark were not furrowed externally. The decorticated stems, in which condition Calamites generally occur, are always ribbed. In some long narrow branchlets proceeded from the transverse joints, while others had branches bearing whorls of small branchlets or long narrow-pointed leaves. Calamites budded out from the base and grew in dense brakes. To support themselves they



190. Woodocrinus macrodactylus.



191. Palæchinus sphæricus.



192. Spirifera striata.

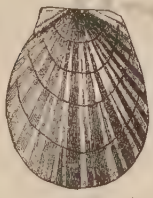
193. Amplexus coralloides.

194. Producta gigantea.

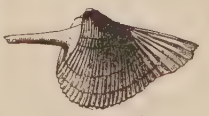
195. Terebratula hastata.

196. Lithostrotion basaltiforme.

197. Phillipsia Derbiensis.



198. Aviculopecten sublobatus.



199. Conocardium minax.

200. Goniatites sphæricus.

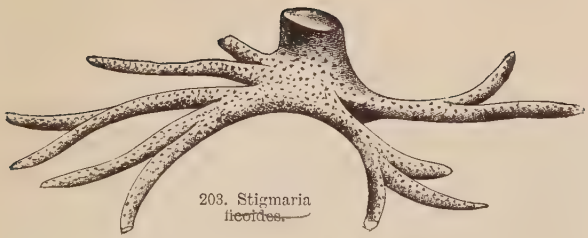
201. Euomphalus pentangulatus.

202. Cœlonautilus cariniferus.

Figs. 190 to 202.—FOSSILS FROM THE CARBONIFEROUS LIMESTONE.

threw out cord-like roots from the lower part of the stem. Some of the forms reached a length of 30 feet. Lepidodendroids (fig. 207) were large arborescent plants apparently allied to existing lycopods or club-mosses. The stems of *Lepidodendron* are covered with leaf-scars arranged in quincunx order, and in their mode of branching they are dichotomous or regularly bifurcating. Some species grew to a height of 60 feet. The seed-cones or spikes (*Lepidostrobus*) of these trees are common fossils. Other prominent lepidodendroids are *Knorria*, *Ulodendron*, etc. The sigillarioids are hardly less abundant than the lepidodendroids. The type genus (*Sigillaria*) shows a fluted stem marked by perpendicular rows of little scale-like impressions or leaf-scars. The roots of this and other trees (*Stigmaria*, fig. 203) are often plentiful in the underclays of coal-seams. *Stigmaria* generally occurs in the form of long rounded or somewhat flattened arms, dotted with numerous small pits or tubercles, from which proceed long cylindrical rootlets. These last, however, are not infrequently wanting, but many underclays are literally crammed with them. Coniferæ (*Dadoxylon*, *Araucarioxylon*, etc.) have been recognised, but they are not so abundant as any of the forms already mentioned. They occur chiefly in sandstones, and now and again in the tuffs of some volcanic cones in Scotland. Nut-like fruits (*Trigonocarpon*) occur often in great profusion, and are conjectured to belong to conifers. It is doubtful whether any cycads occur; some botanists, however, think that the somewhat common genus *Cordaites*, dating from the Devonian, had affinities both with conifers and cycads.

The animal life of the Carboniferous is well represented by an abundant and varied suite of fossils. Amongst Protozoa the most common and widely-distributed forms are foraminifers (*Saccamina*, *Fusulina*, *Nummulina*) which swarmed in the seas, their shells composing no small proportion of some of the limestones. The corals are numerous and varied, the most prominent type being *Lithostrotion* (fig. 196), a compound coral, of which some limestones appear to be almost entirely built up. Simple corals are also extremely common, some of the more common cup-corals being *Clisiophyllum*, *Aulophyllum*, *Cyathophyllum*, *Zaphrentis*, etc. One of the simple cylindrical corals is shown in fig. 193. Amongst tabulate forms are *Alveolites*, *Favosites*, etc. Echinoderms are represented by a great profusion of crinoids (fig. 190), which are among the most important limestone-formers—great thicknesses of that rock appearing to consist of little else than the débris of crinoidal stems, branches, plates, etc. Common genera are *Cyathocrinus*, *Platycrinus*, *Woodocrinus* (fig. 190). The Blastoidea, represented by *Granatocrinus*, etc., now die out. Star-fishes, brittle

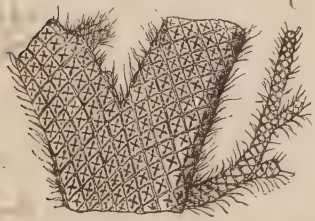


203. Stigmaria ficoides.

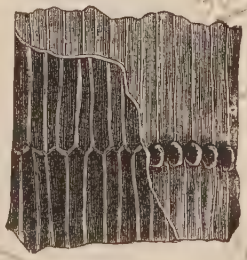
204. Alethopteris lonchitica.

205. Calamites (restored).

206. Neuropteris gigantea.



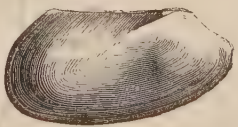
207. Lepidodendron Sternbergi.



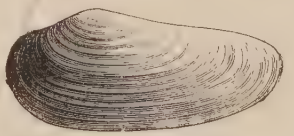
208. Calamites Suckovii.

210. Bellinurus Reginæ.

209. Prestwichia rotundata.



211. Anthracomya modiolaris.



212. Anthracosia acuta.

Figs. 203 to 212.—FOSSILS FROM THE COAL-MEASURES.

stars, and the sea-urchins (*Palæchinus*, fig. 191, *Archæocidaris*), are among the noteworthy forms, the detached plates and spines of the urchins being of common occurrence in limestones and calcareous shales. Of annelids the most important is the little *Spirorbis*. Amongst arthropods we have king-crabs (*Prestwichia*, fig. 209, *Belinurus*, fig. 210), and three or four trilobites (*Phillipsia*, fig. 197), the last representatives of that formerly powerful family. Ostracods are also plentiful, especially such genera as *Beyrichia*, *Leperditia*, etc. They are usually of minute size, their little cases often giving a fissile character to those limestones in which they abound. Phyllopods, such as *Estheria*, *Ceratiocaris*, *Dithyrocaris*, etc., are likewise met with; while long-tailed decapods, such as *Anthrapalæmon*, now and again occur. All the forms now referred to are aquatic, but air-breathing arthropods are also present. Among these are scorpions (*Eoscorpius*, singularly like living forms, but attaining a larger size), spiders, millipedes, and galleyworms. True insects were likewise denizens of the Carboniferous lands, such as various extinct forms of beetles, cockroaches, grasshopper or locust, cricket, white ants, may-flies, spectre-insects, etc.

The Polyzoa are still common forms—the genera *Fenestella* and *Polypora* especially abounding. These and other forms often crowd calcareous shales and limestones. Of the brachiopods the common forms are essentially Palæozoic, such as *Producta* (fig. 194), *Spirifera* (fig. 192), *Strophomena*, *Orthis*, *Athyris*, *Rhynchonella*, *Lingula*, *Discina*, etc. All these genera date from much earlier times. Another characteristic genus is *Terebratula* (fig. 195). The brachiopods although still numerous are no longer a dominating class, their genera and species being outnumbered by those of the lamellibranchs. Among the latter are *Aviculopecten* (fig. 198), *Posidonomya*, *Arca*, *Avicula*, *Modiola*, *Conocardium* (fig. 199), etc.; and the fresh-water bivalves *Anthracomya* (fig. 211) and *Anthracosia* (fig. 212). The gasteropods are numerously represented, *Euomphalus* (fig. 201) and *Pleurotomaria* being common forms. The heteropod form *Bellerophon* and the pteropod genus *Conularia* are also of frequent occurrence. Several air-breathing univalves have been met with, some being true land-snails (*Conulus*) and others closely resembling the existing *Pupa*. Amongst cephalopods the chief are *Goniatites* (fig. 200), *Cœlonautilus* (fig. 202), *Orthoceras*.

Fish-remains occur not infrequently in some limestones, and they are also met with more or less abundantly in the shales, etc., associated with coal-seams and ironstone. The fossils consist chiefly of plates, teeth, defensive spines, and bones. Large and small forms of ganoids are common. Amongst the former are *Rhizodus*, —which was furnished with tusk-like teeth, and had certain

reptilian characters; amongst the smaller forms was *Palæoniscus*, about the size of a minnow. Defensive spines—often beautifully sculptured—suggest the existence of many large predaceous placoid fishes, as do also the numerous broad crushing-plates or teeth which are common fossils in some Carboniferous rocks, (*Cochliodus*, *Psammodus*, etc.) The highest forms of vertebrate life which have been satisfactorily determined are amphibians, some of which seem to have attained a length of seven or eight feet, while others did not exceed as many inches. They resembled in shape the modern salamander, and had relatively weak limbs and a long tail; and the inferior surface of the body was protected by a bony armour, consisting of numerous long plates disposed in oblique rows, which met at an angle along the middle line. The teeth were numerous, and sometimes of large size, like tusks, and they show, when cut across, a complicated "labyrinthine" pattern, due to the rapid folding and plaiting of the wall of the tooth—hence the name of the order *Labyrinthodontia*. The skull was shaped something like that of the crocodile, and, like this animal, the labyrinthodonts appear to have been predaceous. They probably frequented rivers and lagoons, feeding on fishes, crustaceans, insects, and myriapods, and the larger forms sometimes preyed on smaller species, as the bones met with in their *coprolites* (fossil droppings) would seem to show. Among the more important forms are *Archægosaurus*, *Anthracosaurus*, *Dendrerpeton*, etc.

Physical Conditions.—The physical conditions under which the British Carboniferous strata were deposited appear to have been as follows:—About the commencement of the period land prevailed in the Scottish area, although lacustrine conditions, such as obtained in Upper Old Red Sandstone times, still characterised wide regions in the low grounds. The sea, however, spread over the greater part of England, leaving the Silurian area of the Lake district as an island. At the same time another rocky island appears to have extended from North Wales across the Midlands, and it is possible that some land also existed in the south-west of England. Ireland, at the commencement of the period, seems to have been for the most part under water, but rocky islands existed in what are now mountainous and hilly areas in County Down and Wexford and Wicklow, and again in the south-west, the west, and the north-west. In the north of Ireland the lacustrine conditions that characterised Central Scotland at the beginning of the Carboniferous period seem also to have obtained. But in both countries these conditions were erelong exchanged for estuarine and marine. It is along the marginal areas of the Carboniferous sea, as thus roughly defined, that the Lower Limestone Shale of England and the south

of Ireland, and the Calciferous Sandstones of Scotland and the north of Ireland, were accumulated, while the massive Mountain Limestone began to form over the more deeply submerged regions. Thus it is evident that the sedimentary deposits lying at the bottom of the Carboniferous system in the north and the south must be contemporaneous with the lower portions of the thick limestones of the central regions—they are the shallow and deep aqueous formations of one and the same sea.

The whole Carboniferous system, several thousand feet thick, was laid down during a long-continued process of subsidence, but a study of the deposits accumulated along the marginal areas of the sea shows that frequently sedimentation was in excess of subsidence, so that considerable areas became now and again silted up and converted into land, while other regions still continued deeply submerged. The Calciferous Sandstones of Scotland contain the record of many such oscillations of land and sea. Wide areas of what are now the Lowlands were in early Carboniferous times under water. But the estuaries and shallow seas became in many places silted up, and much of Central Scotland then existed as a low flat land, abundantly intersected with numerous ramifying creeks and lakes and lagoons of fresh or brackish water. Tree-ferns, lycopods, calamites, and sigillariæ clothed the flat country, while the creeks and lagoons were slowly silted up with fine mud and decaying vegetable matter (oil shales). In some of the deeper lakes and lagoons ostracods swarmed in myriads and calcareous accumulations took place, in which were gradually entombed the remains of ganoids, and now and again of great cestracionts which may have ascended the sluggish rivers from the sea. Volcanoes were very numerous in Scotland during the whole of the Calciferous Sandstone period. At first most of these were submarine, but some of them existed for so long a time, and poured out so much material, that eventually they became sub-aërial. Besides the large volcanoes of the hills of Haddington, Fife, Stirling, Renfrew, Ayr, etc., numerous little isolated volcanic ejections took place over Central Scotland, after that area had been largely silted up, and converted into the mud-flats and lagoons of the Cement-stone period. That this region was traversed by some considerable rivers, and that now and again wide estuaries opened seawards, is shown by the presence of thick sandstones interstratified with the lagoon silts and calcareous bands, and by the occasional occurrence in such sandstones of large coniferous trees, which were probably carried down from the higher and drier grounds of the highland and upland areas.

While these formations were taking place in the Scottish or northern area, we have evidence that in the south of Ireland and

the south and south-west of England and South Wales, and along the margin of the central barrier of North Wales and the Midlands, great accumulations of silt were gathering over the shallower parts of the sea-floor. Meanwhile the movement of subsidence continued, and erelong the rocky island or barrier referred to became much reduced in size. The sea now lay deep over Central Ireland, and Lancashire, Derbyshire, and Yorkshire, while South Wales and the tracts lying immediately to the south and east were similarly deeply submerged. It was in those regions of deep clear water that the marine fauna of the period flourished most abundantly, and gave rise to the thickest accumulations of limestone. Towards the north the sea gradually shallowed, so that the thick marine limestones of England are represented by a variable series of marine, brackish-water, and terrestrial accumulations in Scotland. Thus, while the larger portion of England and Ireland continued deeply submerged, much of the Scottish area remained as dry land. This was specially the case with the Highlands, and to some extent with the Southern Uplands also. Now and again, however, the sea prevailed not only over the site of the present Lowlands, but even over some considerable portions of the Southern Uplands, and it may well have penetrated far into the mountain-valleys of the Highlands. The Carboniferous Limestone series of Scotland is thus a record of continual oscillations of land and sea—sometimes the one and sometimes the other prevailing—so that we have the former now represented by coal-seams and the latter by limestones, while other associated strata speak of fluviatile and estuarine conditions. The whole series has been laid down during a movement of depression, interrupted perhaps by pauses, when the water areas became silted up and converted into dry land. The volcanic forces which had been so active during the deposition of the Calciferous Sandstone beds still continued to eject lava and fragmental materials, although not in such abundance ; but all such action ceased before the Millstone Grit began to be laid down. Approximately contemporaneous with the Scottish volcanoes were those of Derbyshire, the Isle of Man, and the south-west of Ireland.

The Millstone Grit which overlies the Carboniferous Limestone shows that deep-sea conditions eventually disappeared from the British area. This series of strata is probably largely estuarine and marine, but the occasional presence of fireclays and coals betokens also terrestrial conditions.

The Coal-measures, again, indicate that true marine conditions or open sea ceased to predominate in the British area—the whole series consisting essentially of fluviatile, estuarine, and terrestrial accumulations. Each coal-seam with its underclay represents an old

land-surface, and since many such coal-seams occur one above another, separated by intervening beds of shale, sandstone, etc., it is obvious that the entire series points to accumulation having taken place during a movement of subsidence—a movement which may not have been continuous, but interrupted by longer or shorter pauses. The relative duration of such pauses may possibly be indicated sometimes by the comparative thickness of individual coal-seams, thick coals having required a longer time for their growth than thin seams. But not infrequently coal-seams give evidence of having been subjected to contemporaneous erosion, so that we cannot always be sure that some of the thinner seams may not have been much thicker originally. Again, many thick underclays, abundantly charged with rootlets, have yet no overlying coal-seam —the superficial vegetable covering having been washed away before the overlying strata were deposited.

Coal-seams range in thickness from less than an inch up to 15 feet and more; here and there a number of seams coming together by the thinning out of the associated strata, to form masses not less than 40 feet in thickness. The different varieties of coal are probably due to the character of the vegetable matter composing them. The larger number certainly indicate old land-surfaces, but these were probably in most cases low-lying flats liable to be flooded by rivers or the sea. Some seams, however, such as many "gas-coals," would appear to have accumulated as vegetable slime in lakes and lagoons, for they frequently contain fish-scales and teeth, ostracods, fresh-water or brackish-water shells, etc. Black-band-ironstone was probably formed under similar conditions, for it also often contains fossils, and is frequently associated with gas-coal —indeed, the one rock may be found graduating into the other.

Reference has been made to the evidence of contemporaneous erosion which certain coal-seams exhibit. Some remarkable examples occur in the Scottish coal-fields. Occasionally a seam has been entirely removed over some considerable area—100 to 200 feet across—its place being taken by shale or sandstone. It often happens that in the neighbourhood of such "wants" the seam of coal is doubled, as if the vegetable débris which had occupied the "wants" had been transferred bodily to the surface of the adjacent undisturbed portions of the seam. The strata occupying the "wants" often contain much drifted vegetable matter, and now and again there is considerable confusion, and even contortion, of the beds along the margin of the denuded area. Although the origin of some of these phenomena is hard to explain, there can be little doubt that many of the "wants" are simply old water-channels. Our Coal-measures seem to suggest one or more great rivers, with

numerous effluents and affluents winding through interminable mud-flats—the flats covered with luxuriant vegetation, and interrupted here and there with creeks and lagoons. If such were the general conditions one can readily imagine how, during heavy floods, the large rivers with their effluents and affluents might undermine their banks, or overflow the flats, and cut new channels and courses through morasses, fens, and jungles. We may conceive also how, after unusually heavy rains, or a prolonged rainy season, the spongy vegetable soils, becoming surcharged with moisture, might burst and roll forward upon a comparatively slight slope, thus leaving a "want" in one place, and doubling the thickness of the vegetable covering elsewhere. Or the soils upon an inclined surface might become so slippery with moisture as to cause a slide of the great trees and their undergrowth, and thus produce similar results. But "doublings" are not always accompanied by "wants." In such cases we may suppose that, owing to the irregular and unequal consolidation of underlying sediments and buried soils

Fig. 213.—TWO COAL-SEAMS COMING TOGETHER TO FORM ONE SEAM.

and vegetable growths, some portions of the widespread marsh-lands might become depressed below the general level for a few feet, and these depressions would by and by be filled up by the continuous growth of moisture-loving plants, creeping in, as it were, from all sides. Some of the depressions might at first be occupied by water, forming a series of shallow lakes and pools, in which fine carbonaceous mud might be deposited. Sooner or later, however, they would be filled up with vegetable growth, and thus we might explain not only the abnormal thickening of a coal, but the occurrence also of those thin partings of carbonaceous shale which so often divide such thickened portions into two or more seams. In other cases, where two coal-seams, separated by many feet or yards of strata, afterwards come together by the thinning out of these intervening beds so as to form one seam, the phenomena appear to indicate unequal subsidence. Thus, in fig. 213, the land (A B C) must have been partially submerged—the depressed portion being gradually overlaid by aqueous deposits (*s*). Thereafter these aqueous accumulations were converted into dry land, and the newly-exposed surface eventually became clothed with vegetation, which went to form the upper coal (c^2).

The physical conditions that obtained in the British area during the formation of the Carboniferous system likewise characterised wide regions of what is now the European continent. In France and Belgium we have evidence to show that the deep water of the Carboniferous Limestone period covered an extensive area in those regions, and it probably extended eastward over a large part of Central Europe. In Eastern Europe, however, it seems to have shallowed, for in the strata of those regions limestones hold a subordinate place.

The temperature of the sea appears to have been remarkably equable over a vast area, and we may judge how genial it was from the fact that the same corals that abounded in our own regions and more southerly latitudes in North America also flourished within the Arctic circle, where they were associated with brachiopods that swarmed likewise in the seas of lower latitudes, some of these having been met with as far south as Bolivia. In like manner the coal-seams of the Arctic regions bespeak a genial terrestrial climate, not necessarily a sub-tropical, but rather a moist, warm-temperate one. Many geologists are also inclined to the belief that the atmosphere of the period contained a relatively much larger proportion of carbonic acid. This they infer from the fact that the carbon locked up in our coal-seams must originally have come from the atmosphere, for the plants of the coal-measures no doubt extracted carbonic acid from the air just as plants do in our own day.

So far then as organic evidence enables us to judge the climate of the Carboniferous was singularly uniform. But that ice now and again floated in the seas of the period seems to be shown by the occasional occurrence of erratics in marine strata. Similar erratics, which may likewise have been carried by ice, are met with now and again associated with coal seams in Britain and North America. There are certain Carboniferous breccias in Nova Scotia also which, according to Sir William Dawson, are suggestive of the action of frost, and the same author has referred to the occurrence of large travelled boulders on the slopes of a gigantic esker or gravel-bank of Carboniferous age, where they were probably dropt by drift-ice at a time when the coal-flora was flourishing in adjacent swamps.

VI.—PERMIAN.

In Britain the Permian[1] system rests unconformably upon the Carboniferous strata when these happen to be the underly-

[1] From Perm, a Russian province, in which strata of this age are largely developed.

ing rocks. It consists of two groups, lower and upper, as follows :—

Lower Group, consisting principally of red, brown, purple, and mottled sandstones, reddish clays (marls) and shales, breccias and calcareous conglomerates. This group attains its greatest development (3000 feet) in Staffordshire, Cheshire, and Lancashire, and the Vale of Eden in Westmoreland and Cumberland. In the east of England the same strata do not exceed 250 feet in thickness. Small areas are met with also in Scotland, as in Ayrshire and the valleys of the Nith and Annan in the south. In Ireland they likewise appear in the districts of Downe, Tyrone, and Armagh. In Staffordshire, Worcestershire, Warwickshire, Dumfriesshire, and at Armagh, the breccias have all the appearance of glacial deposits. They consist of angular and sub-angular fragments and occasional large blocks of various rocks, weighing upwards of half a ton. Sometimes the stones are smoothed and marked with striæ like those of glacial origin; possibly, however, these markings may be of the nature of "slickensides." Many of the boulders in the breccias of Staffordshire, etc., have come from the Silurian regions of North Wales, and Sir A. C. Ramsay thinks there can be no doubt that they were transported by ice. He is of opinion, therefore, that these breccias, which in places reach a thickness of 400 feet, indicate a glacial episode during part of the Permian period. In the Scottish area the series contains sheets of lava (melaphyre) and tuff, associated with which are many small volcanic vents or necks filled with agglomerate or with crystalline igneous rocks. Very few fossils occur in this lower group of the Permian, and these consist principally of land plants and labyrinthodont footprints.

Upper Group.—In the east of England this group shows the following succession :—

Red sandstones, clays, and gypsum .	50 to 100 feet.
Magnesian limestone . . .	500 to 600 ,,
Marl-slate	about 60 ,,

In the midland and north-western districts the arenaceous deposits are developed at the expense, as it were, of the Marl-slate and Magnesian Limestone, the sandstones attaining a thickness of several hundred feet, while the limestone and its underlying marl have thinned out to a few yards in thickness, and are generally represented by a series of thin calcareous layers associated with variegated sandstones. The most important member of this upper group of the Permian is the Magnesian Limestone, which, where best developed, consists of a series of yellow and brown, fine-grained and compact, crystalline, brecciated, and earthy dolomites. Some beds

are concretionary, resembling piles of cannon balls, or heaps of turnips, or bunches of grapes, while others are oolitic. The Marl-slate is a brownish shale, often containing courses of magnesian limestone. The fossils of this group are abundant, and all, with the exception of a few drifted land-plants, are marine.

Foreign Permian.—In Germany the Permian is composed of two members, hence termed Dyas—the Zechstein and Kupferschiefer corresponding to the upper, and the Rothliegende to the lower, group of Britain. These strata are typically developed in the Harz and the Thüringerwald. The Rothliegende ranges from 1200 to 5000 feet in thickness, and consists chiefly of red and reddish brown, and sometimes greyish conglomerates, sandstones, and shales, with occasional lenticular layers of limestone and dolomite, and now and again bituminous shales. Associated with such aqueous strata are sheets of porphyrite, melaphyre, quartz-porphyry, etc. The Zechstein or upper group comprises two well-marked members—the *Kupferschiefer*, which is the equivalent of our Marl-slate, and the *Zechstein*, which corresponds to our Magnesian Limestone. The Kupferschiefer (2 feet thick) has long been famous for its ores of copper and other metals, which are found coating and replacing the numerous remains of fish, etc., with which the shale is charged. The Zechstein, an argillaceous, thin-bedded, compact limestone, from 16 to 95 feet thick, is abundantly fossiliferous. It is overlaid by a crystalline, granular, and fine-grained sandy-like dolomite, from 6 to 65 feet thick, above which comes a variable series of beds of anhydrite, gypsum, rock-salt, marl, and bituminous limestone and shale. The German Dyas therefore presents the same general features as the Permian of Durham and the east of England.

In Russia the Permian—consisting of horizontal strata of conglomerate, sandstone, shale, and occasional seams of limestone, gypsum, rock-salt, and thin coals—covers an area of more than 15,000 square miles, extending from near Moscow to the Urals. The general facies of the strata is like that of the Permian of the Midlands and north-west of England—limestone being quite a subordinate formation, and often wanting.

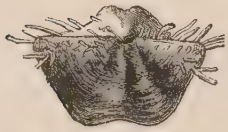
In North America the Permian seems to be represented chiefly in the western part of the continent, where it consists of a series of marine strata that rest conformably upon and graduate down into the Carboniferous, so that no hard and fast line can be drawn between the two systems.

Life of the Period.—The Permian strata as a whole are not rich in organic remains, and these occur chiefly in the limestones and their associated greyish shales, etc. The red-coloured strata which form the greater portion of the system are for the most part

unfossiliferous. Comparing the flora of the Permian with that of the preceding period, the former appears poor and meagre. But the poverty of the flora may be only apparent—the conditions for its preservation not having been so favourable as during Carboniferous times. Its affinities are decidedly Palæozoic—some of the species and many of the genera being common Carboniferous forms. Upon the whole, it may be considered as an impoverished continuation of the Carboniferous flora. Many of the forms characteristic of that flora were now on the wane—the lepidodendroids and sigillarioids not being met with in strata younger than the Permian. The most common plants are ferns—both herbaceous and arborescent—many of the genera being Carboniferous, while others, such as *Callipteris*, have not yet been detected in the Coal-measures. Conifers were likewise numerous, one characteristic form being the yew-like *Walchia*, and another hardly less so—the cone-bearing *Ullmannia*. Here also we meet with transitional types allied to conifers and cycads (*Nöggerathia*).

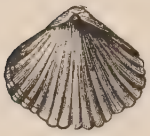
The animal life of the period is somewhat better represented, but it too appears impoverished when contrasted with that which flourished during the preceding period. The numerous rugose corals of earlier Palæozoic times are now all but extinct, and even tabulate forms are feebly represented. The echinoderms consist chiefly of a few crinoids. Amongst crustaceans the most important is a small crab (*Hemitrochiscus*), the earliest representative of the "short-tailed" decapods. Polyzoa are fairly numerous, such forms as *Fenestella* (fig. 215), *Synocladia*, etc., being common in the Magnesian Limestone. Amongst brachiopods the most abundant types are *Producta* (fig. 214), *Camarophoria* (fig. 216), *Spirifera* (fig. 220), *Strophalosia* (fig. 218), and *Lingula* (fig. 217). Lamellibranchs appear in somewhat larger numbers than brachiopods. Characteristic genera are *Schizodus* (fig. 219), *Solemya*, *Gervillia*, etc. Gasteropods are feebly represented; old forms still occurring, such as *Murchisonia* and *Pleurotomaria;* the same is the case, but in even a more marked degree, with cephalopods, the only Permian forms known belonging to *Orthoceras*, *Cyrtoceras*, and *Nautilus*. Fish-remains occur in comparative abundance in the Kupferschiefer of Germany, and now and again in the corresponding Marl-slate of this country. The principal genera are *Palæoniscus* (fig. 221) and *Platysomus*. We may note also the first unequivocal traces of the genus *Ceratodus*. Amphibians seem to have abounded. These are known partly through skulls and detached bones, but more commonly through their footprints. They are all labyrinthodonts; characteristic forms being *Archægosaurus*, *Branchiosaurus*, *Pelosaurus*, etc. True reptiles (*Proterosaurus*) now make their first appearance.

Physical Conditions.—In the British area, and in most parts of Europe where the Permian system is developed, the strata are unconformable to the Carboniferous. The unconformity is not violent or strongly discordant, but quite sufficiently well-marked.



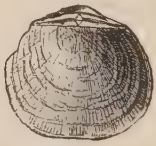
214. Producta horrida.

215. Fenestella retiformis.

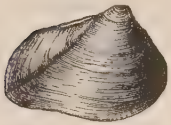


216. Camarophoria Schlotheimi.

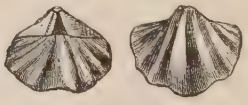
217. Lingula Credneri.



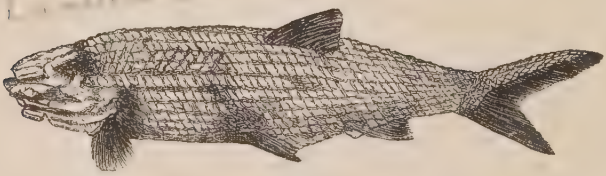
218. Strophalosia lamellosa.



219. Schizodus Schlotheimi.



220. Spirifera alata.



221. Palæoniscus comptus.

Figs. 214 to 221.—FOSSILS FROM THE PERMIAN.

It is evident, then, that towards the close of Carboniferous and the beginning of Permian times, considerable earth-movements took place which resulted in the disappearance of the sea from wide regions in Europe, and in the eventual isolation of various large

tracts, which thus became inland seas or salt lakes. According to Sir A. C. Ramsay, the petrological character of the Permian rocks points to deposition in such lakes—the red and variegated sandstones, the dolomitic limestones, and the associated gypsum and rock-salt, are just such as would be accumulated in salt lakes and inland seas like the Caspian. In closed seas of that kind we should not expect an abundant fauna, for the conditions are not favourable to life. Now the fauna of the Permian seas was certainly an impoverished one, and not only so, but the forms are often dwarfed and stunted. One or more such inland seas covered large areas in what is now Central and Northern England, and extended into Southern Scotland and the north of Ireland. And similar large inland seas existed in Middle and Eastern Europe. It is quite in keeping with this view that plentiful footprints and other indications of littoral conditions, such as worm-tracks, sun-cracks, rain-pittings, ripple-marks, etc., should be present. The level of the lakes would often be abnormally lowered in summer, leaving wide tracts exposed, over which amphibians and reptiles would crawl; and the footprints impressed in the clays and muddy sands, when these dried and hardened, would readily be preserved under the new accumulations which would be formed when, during rainy seasons, the water again increased in volume. Volcanic action was rife in Scotland and also in Germany, and it is believed that the abundant well-preserved fish-remains which occur in the Kupferschiefer owe their presence to the sudden poisoning of the water by mineral springs connected with the volcanic disturbances of the period. It is not necessary to suppose that all the seas remained permanently closed. Some may have had occasional connection for longer or shorter periods with the open ocean, as, for example, during the formation of the thicker limestones; but, taken as a whole, the general character of the strata is that of accumulations formed in inland seas.

The climate of the period may be inferred from the aspect of the fauna and flora to have been mild and genial; but the presence of the coarse breccias, with their scratched stones and erratics, shows us that during one stage at least ice-rafts, and perhaps icebergs, sailed in the latitude of Central England.

GENERAL CHARACTER OF PALÆOZOIC FAUNAS AND FLORAS.

In summing up the general character of Palæozoic faunas and floras we find that these were distinguished by the large number of what have been termed *synthetic* or *comprehensive* types, that is to

say, types which, while belonging fundamentally to some particular division or group of the animal kingdom, yet present in their structure characteristics of one or more contemporaneous or as yet non-existing types. Among such intermediate forms may be mentioned the Labyrinthodonts, which were urodele amphibians, presenting many piscine and reptilian characteristics. The Ganoids, again, although true fish s, yet by their teeth and certain structures recall the reptiles; and they also have some affinities to the Chimæridae. The Trilobites seem to be related to the phyllopods, the xiphosura (king-crabs), and the isopods. The Brachiopods, which formed so prominent a feature in the Palæozoic faunas, have affinities both with molluscs and annelids. So also the few Insects of which we have any trace seem to have been composite or intermediate forms, and the same might be said of many other Palæozoic types, both animals and plants. The Lepidodendroids, for example, combined characteristics of club-mosses and conifers. Of the Palæozoic intermediate or comprehensive types, many became extinct before Mesozoic times; others survived for longer periods; and some (such as ganoids and brachiopods) are still represented in the living world, although greatly impoverished. Other intermediate forms, particularly in the higher grades of the animal kingdom (reptiles and birds), came into existence and flourished in prodigious numbers during Mesozoic times, but died out before the beginning of the Cainozoic era.

The most prominent animal types of Palæozoic times were Graptolites, Rugose Corals, Brachiopods, Crinoids, Pteropods and Heteropods, Nautilid Cephalopods, Trilobites, Eurypterids, and Heterocercal Ganoids. Graptolites ranged from the Cambrian into the Devonian (Lower Old Red Sandstone), attaining their maximum in the Lower Silurian. Rugose corals, which were not known in the Cambrian, swarmed in Silurian, Devonian, and Carboniferous seas, but were reduced to a very small number in Permian times. At the present day this eminently Palæozoic group is represented by only two genera. Crinoids first appear in the Cambrian, are numerous in Silurian and Devonian strata, but more abundant still in the Carboniferous. After this they begin to decline, although they were still numerous in Mesozoic seas. Brachiopods, commencing in the Cambrian (chiefly with inarticulate genera) abounded all through Palæozoic time, but culminated in the Upper Silurian period. They were still very numerous in the Devonian and Carboniferous seas, but less abundant in those of the Permian period. Pteropods and Heteropods were likewise common Palæozoic forms. They were more numerous in Upper Cambrian and Silurian times than during the Devonian and Carboniferous periods. Nautilid

cephalopods (represented by *Nautilidæ* proper and *Orthoceratidæ*) first appear in the Upper Cambrian, and seem to culminate in the Silurian, but they continued to abound in the Devonian and Carboniferous seas, becoming reduced in those of the Permian period. Trilobites are a very characteristic Palæozoic type. Appearing in the Cambrian, they attain their maximum in the Silurian, wane in the Devonian, and die out in the Carboniferous. Over 1600 species are known. Eurypterids are also exclusively Palæozoic in their range. They seem to culminate in the Upper Silurian and Old Red Sandstone, and become extinct in Carboniferous times. Ganoids, with heterocercal tails, make their first appearance in Upper Siluran strata, and reach their maximum in the Old Red Sandstone. The great order of the Sharks and Rays likewise dates back to Upper Silurian times.

Amongst plants the prominent Palæozoic types are cryptogams —Lepidodendroids and Sigillarioids being exclusively Palæozoic.

Many Palæozoic species were characterised by their large size as compared with the species of the same groups that belong to later times. Thus some pteropods, cephalopods, ostracods, phyllopods, eurypterids, trilobites, and insects were larger than any of the allied forms of our own day. The Palæozoic amphibians also much exceeded in size any living representatives of their class. Again, our modern club-mosses, which are insignificant plants, either trailing on the ground or never reaching more that two feet in height, were represented in Palæozoic times by great arborescent forms.

There is all through the Palæozoic strata abundant evidence of a gradual coming in and dying out of species, the changes being most gradual in the case of conformable strata, while unconformities are marked by an apparent more or less abrupt disappearance of old and sudden introduction of new forms. Innumerable Palæozoic genera became quite extinct before the beginning of Mesozoic times, while not a few lived on, and some have even persisted to the present day. This is most marked among the lower types of animal life. Thus the Palæozoic foraminifers closely resemble living forms, and some of the genera seem to be the same. Again, amongst molluscoids and molluscs such well-known Palæozoic genera as *Crania*, *Discina*, *Terebratula*, *Ostrea*, *Avicula*, *Leda*, *Dentalium*, *Nautilus*, etc., are still living in our seas.

EVOLUTION OF CONTINENTAL AREAS IN PALÆOZOIC TIMES.

We note, as we follow the stony record from the beginning to the close of Palæozoic times, that amongst the numerous oscillations

of land and sea which characterised the European area, terrestrial conditions nevertheless persisted in the northern part of the continent. The earliest land-surfaces, formed of Archæan rocks, prevailed from the first in the North British and Scandinavian regions. During Cambrian times we have evidence of great lacustrine formations taking place in the north of Scotland, and possibly similar lacustrine conditions may have obtained in the Welsh area at the commencement of the Cambrian period. Eventually, however, submergence set in and continued with minor interruptions up to the close of the Lower Silurian period. A movement of upheaval now ensued, and considerable areas of sea were converted into dry land. The chief land-areas probably still lay in the north (Scotland), while a number of islands dotted the surface of the Upper Silurian sea, in what is now Wales. And similar archipelagoes may have existed in those parts of the European area where Archæan schists and older Palæozoic rocks occur. Many of these islets, however, seem to have been eventually submerged in the sea of later Silurian times. The Silurian period came to a close with the re-elevation of large areas which had formerly been overflowed. The Old Red Sandstone system points to the existence of very considerable land-tracts, chiefly, as before, in the north part of the European area, while the sea at the same time extended over Southern Britain and wide regions in Middle Europe. In early Carboniferous times the depressions, formerly occupied by the inland seas and lakes of the Old Red Sandstone period, were invaded by the ocean ; but a wide land-surface still persisted in the north of Scotland and Scandinavia. By and by the marginal areas of the Carboniferous sea became silted up, and eventually that ancient Mediterranean disappeared, and was represented by a series of salt lakes or inland seas, stretching across a great continental area, from Central Britain into Germany. So far then as our present knowledge goes that part of the European continent which was the earliest to be evolved lay towards the north-west and north. All through the Palæozoic era a land-surface would seem to have endured in that direction—a land-surface from the denudation of which the marine sediments of the bordering regions were derived. But when we reflect on the vast thickness and horizontal extent of those sediments we can hardly doubt that the primeval land must have had a much wider extent towards the north and north-west than is the case with modern Europe. The source from which the older Palæozoic marine sediments of the British Islands and Scandinavia were obtained must for the most part be now submerged. In later Palæozoic times land began to extend in the Spanish peninsula, Northern France, and

Middle Europe, the denudation of which doubtless furnished materials for the elaboration of the contemporaneous strata of those regions. In few words, then, we may say that while after Archæan times land prevailed in the north and north-west, marine conditions predominated farther south. Ever and anon, however, the sea vanished from wide regions in Central Europe, and was replaced by terrestrial and lacustrine conditions. Further, as none of the Palæozoic marine strata indicates a very deep ocean, but all consist for the most part of accumulations formed at moderate depths, it follows that there must have been general subsidence of our area to allow of their successive deposition—a subsidence, however, which was frequently interrupted by long pauses, and sometimes by movements in the opposite direction.

In America the evidence goes to show that, as in Europe, the earliest dry lands appeared in the north—in the regions now occupied by Archæan rocks. During the progress of Palæozoic time the terrestrial area gradually extended southward.

The climate of the era, if we may rely upon the testimony of the extinct faunas and floras, was singularly uniform. But the occasional appearance of traces of ice-action may lead us to suspect that, as happened in later times, there may have been now and again epochs during which the climatic conditions were less uniformly genial.

CHAPTER XXIII

HISTORICAL GEOLOGY—SECONDARY OR MESOZOIC SYSTEMS.

Triassic system : life ; physical conditions—Jurassic or Oolitic system : life ; physical conditions—Cretaceous system : life ; physical conditions—General character of Mesozoic faunas and floras—Evolution of continental areas in Mesozoic times.

I.—TRIASSIC.[1]

THE Secondary or Mesozoic formations of the British area are separated from those of Palæozoic age by a distinct unconformity. The lowest member of the series—the Triassic—rests on the denuded edges of the Permian and older Palæozoic strata—all of which had been upheaved, dislocated, metamorphosed in part, and extensively denuded before the Triassic began to accumulate. The strata of this system circle round the outskirts of the present high grounds of Wales and the north of England, and overlap the Permian and Carboniferous strata in such a way as to suggest that in its main features the configuration of Wales and Northern and Central England in Triassic times had even then assumed much of its present appearance. Such unconformity implies the lapse of long ages, during which the faunas and floras would necessarily undergo many modifications. Consequently we might have anticipated that the fossils of the Trias would differ markedly from those of the Palæozoic rocks. They show us, indeed, that most of the great Palæozoic types had become quite extinct, while many new races had been ushered in, which kept their place down to the close of Mesozoic times. The Trias of Britain shows the following succession :—

RHÆTIC (20 to 150 feet)	Penarth beds, dark shales, grey and greenish marls, and grey limestone. These form the passage-beds into the next succeeding system (Jurassic).

[1] This term has reference to the threefold grouping of this system in Germany. In England the Triassic and Permian were formerly grouped together as "New Red Sandstone," a designation which, when applied now, is restricted to the Trias.

Upper Trias or Keuper (800 to 3250 feet)	New Red Marl.—Red and grey shales and marls and thin sandstone bands, with layers of rock-salt and gypsum. Lower Keuper Sandstone.—White sandstones and red marls, etc.
Middle Trias . .	(Wanting in Britain.)
Lower Trias or Bunter (80 to 2000 feet)	Upper Mottled Sandstone.—Soft red and variegated sandstones. Pebble beds.—Pebbly sandstones and conglomerates. Lower Mottled Sandstone.—Soft, red, and variegated sandstones.

These strata occupy a considerable area in the central plains of England from which one long belt stretches north from Nottingham to the valley of the Tees, while another band extends down the valley of the Severn into Devonshire. The red beds underlying the Rhætic vary much in thickness, attaining their greatest development, 5000 feet or so, in the north-west (Cheshire district), and in the south-west (Devonshire district), where they are probably not less than 3000 feet thick. The Rhætic beds are rarely thicker than 20 to 150 feet, and pass up conformably into the overlying Lias. Small areas of red sandstones occurring in Dumfriesshire and near Elgin on the Moray Firth, have been referred to the Trias, and strata of the same age are met with in the north of Ireland.

Foreign Trias.—Triassic strata are well developed in Central Europe, particularly in Germany. They occur at the surface over a large extent of country, between the Thüringerwald in the east and the Vosges Mountains in the west; and between Basel in the south and Hanover in the north. North of that region they continue under younger formations, but appear again and again at the surface where these latter are wanting; while various borings in the flat lands of North Germany show that they extend east as far as the Vistula. Trias occurs likewise in Heligoland and in the southern part of Sweden. The strata of the German Trias form three well-defined groups, as follows:—

3. Keuper: a series of red and variegated marls (containing beds of laminated clay, and layers of gypsum and anhydrite, and now and then saliferous clays and rock-salt), resting on fine-grained grey, sometimes greenish, sandstones, shales, and marls, abundantly charged in places with plant-remains.

2. Muschelkalk: limestone, from 550 feet to 1100 feet in thickness; the upper portion pure and abundantly fossiliferous; the middle and lower portions often dolomitic, and associated with

rock-salt, gypsum, and anhydrite—few fossils occur in these portions.

1. Bunter: red sandstones and marls, with some gypsum and, occasionally, rock-salt, and dolomite; fossils are chiefly land-plants, footprints of labyrinthodonts, etc.

The Trias of the Eastern Alps differs much, both petrologically and palæontologically, from that of Germany. It attains a thickness of many thousand feet, and has been divided into three groups, as follows:—

Rhætic: consisting chiefly of fossiliferous limestone and shale and unfossiliferous dolomite.

Upper Trias: a very variable series of strata, comprising thick limestones and dolomites, thinner limestones and calcareous shales, sandstones, marls, etc. Seams of coal associated with fresh-water beds occur at one horizon in the series: all the other strata are marine, and often highly fossiliferous. Contemporaneous igneous rocks are associated with this division of the Alpine Trias.

Lower Trias: chiefly limestones, all fossiliferous.

Thus in Western and Central Europe, we have two well-defined types—the English, in which the Muschelkalk is wanting; and the German, in which that division is strongly developed. In the Alpine regions we have a third type, so divergent from those of England and Germany as to indicate very different physical conditions. In France isolated areas of Trias occur, some of which show the English and some the German type. In Spain and Portugal again we have representatives of the German and Alpine types.

In North America the Trias is well developed. It appears in the Atlantic-border region, between the Appalachians and the coast, in long narrow strips which have the same trend as those mountains. The strata consist chiefly of red sandstones, with occasional shales, conglomerates, and impure limestones. The principal areas where these rocks occur are Nova Scotia and Prince Edward's Island; the Connecticut valley; west side of the Hudson River, and south-west through Pennsylvania into Virginia; North Carolina. Brick-red sandstones and marls believed to be of the same age cover wide regions in the Western Territories, extending from the eastern borders of the Rocky Mountains across into Alaska, British Columbia, and California. Ripple-marks, rain-prints, mud-cracks, footprints and tracks, and other evidence of shallow-water conditions are of frequent occurrence, more especially in the red beds of the Connecticut valley. The red beds all through the continent are generally unfossiliferous—the chief fossils being a few land-plants (cycads, conifers, and ferns). Animal life is represented

chiefly by the footprints of labyrinthodonts and reptiles, the latter being impressions of three-toed feet, having a strong bird-like appearance. Upon the whole, the American strata above referred to resemble the English type of the Trias. On the Pacific slope, however, in Northern California and Mexico, the strata yield a plentiful marine fauna, and present the type of the Alpine Trias.

Rocks of Triassic age have been recognised in Spitzbergen, in the Himalaya; and again in South Africa, in New South Wales, Victoria, and Queensland, where the series contains coal-beds.

Life of the Period.—The predominant plants are cycads (*Pterophyllum*, *Zamites*, etc.), other common forms were horse-tails (Equiseta), ferns (including a few Carboniferous genera), and coni-

222 Mastodonsaurus giganteus.

223. Estheria minuta.

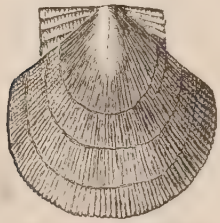
Figs. 222, 223.—FOSSILS FROM THE KEUPER.

fers, represented by cypress-like genera, such as *Voltzia*, which is one of the most common Triassic fossils.

In the red beds of the Trias few organic remains occur, our knowledge of the animal life of the period (more especially the invertebrates) being derived from the Muschelkalk, the Rhætic, and the marine strata of the Alpine series. Foraminifers, sponges, and representatives of the modern group of the star-corals are obtained in these, and echinoderms are fairly numerous. One of the most beautiful forms is the lily encrinite (*Encrinus liliiformis*) of the Muschelkalk. Molluscs are common, particularly lamellibranchs and gasteropods. Amongst the former are *Myophoria* (fig. 229), *Avicula* (fig. 227), species of *Pecten* (fig. 224), and *Cardium* (fig. 226), etc. The important Palæozoic family of the Productidae is no longer represented, the commoner brachiopods being *Terebratula*, *Discina* (fig. 228), etc. A number of Palæozoic genera of gasteropods (*Loxonema*, *Murchisonia*, *Euomphalus*, etc.) are also present, commingled with newer forms. The same is the case with the cephalopods, such old genera as *Orthoceras*, *Cyrtoceras*, and *Goniatites* occurring along with *Ceratites* and various species of the

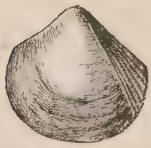
great tribe of *Ammonites*. This remarkable commingling of Palæozoic and Mesozoic genera is most notable in the Alpine Trias. In the same strata occur the first traces of dibranchiate cephalopods, represented by internal skeletons (*Belemnites*).

The Triassic fishes are ganoids and placoids—the latter represented by spines (fig. 230), and palate-teeth (*Ceratodus*, fig. 225), like



224. Pecten valoniensis.

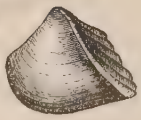
225. Ceratodus parvus.



226. Cardium rhæticum.

227. Avicula contorta.

228. Discina Townshendi.



229. Myophoria postera.

230. Nemacanthus monilifer.

Figs. 224 to 230.—FOSSILS FROM THE RHÆTIC.

those of the modern mud-fishes (Dipnoi) which are vegetable feeders.

The amphibian labyrinthodonts appear to have abounded, and some were noteworthy for their great size—the skull of *Mastodonsaurus Jægeri* measuring over three feet in length by two in breadth. These creatures are known chiefly through their footprints (fig. 222), which are often plentiful in the red beds of the Trias. Lizard-like reptiles (*Telerpeton*, *Hyperodapedon*, *Rhyncosaurus*) were also numerous, while Crocodiles, represented by the *Stagonolepis* of the Elgin sandstones and other forms, now appeared for the first time. The same is the case with the extinct group of the Dino-

saurians—terrestrial reptiles, some of which could walk on their hind feet, which were often only three-toed, their front feet being four-toed. The footprints of these Dinosaurs are very numerous in the sandstones of the Connecticut valley, and the three-toed impressions were at first supposed to be those of gigantic birds. It is quite possible, indeed, that some of the three-toed footprints may really be avian. They vary in size—the largest being nearly two feet long —or four times as large as that of the ostrich. Swimming reptiles (*Nothosaurus*, etc.) have also been recorded from Triassic strata. The Anomodontia are represented by *Dicynodon*, a reptile provided with a horny beak and two large tusk-like teeth in the upper jaw. The Trias is further remarkable for having yielded the earliest relics of mammalia. These are only known through their teeth and lower jawbone, which have been met with both in Europe and North America. They seem to have been small marsupials with some affinities to the little Banded Ant-eater of Australia. The European form is *Microlestes*, and the American, *Dromatherium*.

Physical Conditions.—The British Triassic strata afford evidence of very much the same kind of conditions as obtained during the deposition of the red beds of the preceding Permian. According to Ramsay there can be no doubt that they were accumulated in a great inland salt-lake from the waters of which sodium chloride (rock-salt) and other chemically-formed materials were precipitated. This great inland sea covered a large part of England, and seems to have extended north into Southern Scotland and across the area of the Irish sea into the north-east of Ireland. It is possible also that the same sea stretched across what is now the English Channel into Northern France. Another lake is indicated by the red sandstones of Elgin. The lands surrounding these lakes were clothed with cypress-like evergreens, and their shores were frequented by labyrinthodonts and various reptiles—the highest forms of vertebrate life being represented by small marsupials. The briny waters were unfavourable to life, and we have consequently but little trace of any aquatic fauna, which appears to have consisted chiefly of small phyllopods (*Estheria*, fig. 223) and fishes. Eventually the lacustrine areas became largely silted up, and then subsidence of the land took place, so that the sea invaded the area and occupied some of the shallow depressions. In these marine areas the Rhætic deposits accumulated.

On the Continent the evidence supplied by the German Trias shows that during a large part of the period an extensive inland sea extended westwards from the Thüringerwald across the Vosges into France, and stretched northwards from the confines of Switzerland over what are now the low grounds of Holland and Northern

Germany. In this ancient sea, the Harz Mountains formed a rocky island. In the earlier stages of the period the conditions seem to have been much the same as in the English area, but the thick Muschelkalk with its numerous marine forms seems to indicate an influx of water from the open sea. Afterwards, however, this connection was closed, and the subsequent accumulations point to increasing salinity, during which depositions of gypsum, rock-salt, etc., took place, while the marine fauna disappeared. Towards the close of the period, after the great lake had been largely silted up, a partial influx of the sea took place, when deposits containing a fauna comparable to that of the English Rhætic were laid down in some areas.

The Alpine Trias, which is mostly marine, shows that while continental and lacustrine conditions obtained in Central and Northern Europe, an open sea existed in the more southerly regions of the Continent. In these deposits we have a remarkable commingling of Palæozoic and Mesozoic molluscs, proving that the break between the Permian and Trias which is so notable in Britain was only local, and that in the open sea many characteristic Palæozoic forms continued to flourish, and were only gradually replaced by newer types.

In North America we have a repetition of the same general conditions—the deposition of red sandstones, etc., in inland basins —and the accumulation of fossiliferous strata in an open sea.

Of the climate of Triassic times not much can be said. Judging from the fact that strata, containing characteristic forms of the period, are met with in Spitzbergen, we might infer that the conditions were generally genial. But the occurrence of scattered erratic blocks in the Trias of Devonshire may possibly point to the existence at some time during the period of colder conditions, since it is hardly likely that the appearance of ice-rafts so far south could be contemporaneous with the flourishing of a Triassic fauna in the Arctic seas.

II.—JURASSIC OR OOLITIC.[1]

The Jurassic strata of Britain are well developed in England, covering a large area in Yorkshire between the mouth of the Tees and Filey Bay, and extending south from the river Humber along the western borders of the great flats of Lincoln and Cambridge, from which they sweep south-west in a broad belt across the Midland Counties to the Bristol Channel and the shores of the English

[1] *Jurassic*, from the *Jura* mountains, where rocks of this age are well developed. *Oolitic* (egg-stone), from the structure of many limestones of this age, which are composed of round grains like the roe of a fish.

Channel between Lyme Regis and Durlestone Head. Strata of this age are only sparingly shown in Scotland, occurring in patches in some of the Western Islands and near Brora on the east coast of Sutherland. In Ireland Oolitic strata are likewise very poorly developed, being visible only near Larne and Portrush in Antrim.

The English strata are grouped as under :—

	Max. thicknesses.
4. Portland or Upper Oolites . .	1100 feet.
3. Oxford or Middle Oolites . .	850 „
2. Bath or Lower Oolites . . .	1000 „
1. The Lias	1450 „
	4400 feet.

The Lias overlies the Rhætic conformably, and is composed chiefly of laminated clay, with occasional thin beds of blue or grey argillaceous limestone. Here and there the beds are somewhat arenaceous, especially about the middle of the series (Marlstone), where ironstones also occur, as at Cleveland. The top of the Lias is capped with beds of sand.

The Bath or Lower Oolites include the following groups in ascending order :—

(*a*) The *Inferior Oolite:* a series of arenaceous limestones and calcareous freestones and grits, attaining its greatest thickness (250 feet) at Cheltenham, and thinning away towards Oxford.

(*b*) The *Fuller's Earth:* chiefly blue and yellow clays, shales, and marls ; 150 feet thick near Bath, 400 feet thick in Dorsetshire ; does not occur in the eastern and north-eastern counties.

(*c*) *Great* or *Bath Oolite:* a series of calcareous oolitic sandstones, sandy flags, and blue limestones which are sometimes very flaggy, and locally called *slates* (Stonesfield Slate). Towards the top of the series the limestones are white and thick-bedded.

(*d*) *Forest Marble and Cornbrash:* a series of clays, sands, and limestones, some of which are oolitic, others mere masses of shells. [In Yorkshire the Lower Oolites (800 feet in thickness) consist principally of sands and clays with seams of coal and ironstone.]

The Oxford or Middle Oolites comprise two groups :—

(*e*) *Oxford Clay:* a dark grey or blue clay, containing, in some places in its lower portions, calcareous sandstones (Kellaways Rock) ; occurs generally throughout all the Jurassic areas in England.

(*f*) *Coral Rag:* variable mass of limestones, some highly oolitic, others made up of corals, yet others fine-grained ; these limestone-beds are usually underlaid and overlaid by calcareous sandstones and grits.

The Upper or Portland Oolites consist of three groups, which, in ascending order, are as follows :—

(*g*) *Kimeridge Clay:* generally a shaly clay, with occasional bands of calcareous grit or ferruginous oolite. Sometimes it becomes highly carbonaceous, approaching to the character of an imperfect shaly coal.

(*h*) *Portland Beds:* a series of sands and sandstones passing up into calcareous grit and limestone.

(*i*) *Purbeck Beds:* distinguished from all the preceding groups in being mostly of fresh-water origin. They contain also traces of old land-surfaces (dirt-beds), consisting of vegetable soil with the roots and stems of fossil plants.

The several groups now described are apt to vary much as they are followed along the outcrop—thickening or thinning irregularly and sometimes dying out altogether. In this respect they differ from most of the great Palæozoic formations, which usually maintain the same character over wider areas. Nevertheless, looked at broadly, the Jurassic of England may be said to consist of successive alternations of clay deposits and calcareous accumulations which are more or less persistent throughout the area occupied by the system.

Foreign Jurassic.—Crossing the Channel to France we find Jurassic strata well developed. In the north the beds are evidently the continuations of those which crop out on the English coast. They form a ring-like zone or belt which sweeps round the Cretaceous strata of the Paris basin ; underneath which the Jurassic beds doubtless continue. Farther south another belt of the same formation surrounds the Central Plateau of crystalline rocks. In Germany the Jurassic covers several extensive areas—the most continuous of which are in North-west Germany, in Franconia and Swabia, and in Upper Silesia. Much of the system in the flat lands is concealed under glacial and fluvio-glacial accumulations. The chief subdivisions of the Jurassic in Germany are Malm, White Jura (= Middle and Upper Oolites of England), Dogger or Brown Jura (= Lower Oolites of England), and Lias or Black Jura (= Lias of England). Jurassic strata occupy wide tracts in Central Russia, and more or less isolated areas occur in the Caucasus, the Carpathians, etc. One of the most important Jurassic regions, however, is that of the Jura Mountains, extending between Basel and Geneva. Narrow and broader belts of the same strata are also met with here and there along the south-west and north flanks of the Alps. These rocks are often much contorted, faulted, and metamorphosed. In North America Jurassic strata have been recognised in the Sierra Nevada and among the Rocky Mountains (Black Hills, Laramie Mountains) ; the strata in Colorado having yielded many

remarkable reptilian remains. Further, Jurassic rocks occur in South America, in Spitzbergen and Siberia, in India (Cutch), in Australia, New Caledonia, and New Zealand.

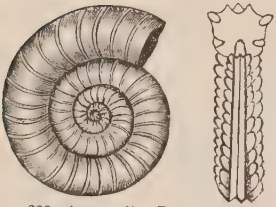
Life of the Period.—The land-plants consist mainly of ferns, cycads (fig. 269), and conifers, with occasional traces of endogenous plants, consisting of fruits belonging apparently to forms allied to the screw-pines.

The lower classes of the animal kingdom are abundantly represented by foraminifers and sponges, by a great variety of corals, by crinoids (both fixed and free forms), by star-fishes, sea-urchins, etc. Corals (fig. 264) are especially numerous, and mostly belong to the reef-building family of star-corals. Many of the limestones of the period, particularly those of the Coralline Oolite and its continental equivalents, are simply old coral-reefs. Amongst crinoids *Pentacrinus*, *Extracrinus* (fig. 234), and *Apiocrinus* are characteristic forms. Many genera of sea-urchins occur, such as *Acrosalenia* (fig. 249), *Cidaris* (fig. 261), etc., and with these were associated numerous star-fishes and brittle-stars. The Arthropoda are represented by crustaceans, arachnids, and insects. The most prominent crustaceans are the long-tailed decapods, to which belong our existing lobsters and prawns, besides which true crabs also occur. True spiders and myriapods are known as Jurassic forms, and many insect-remains have been obtained. Amongst these were cockroaches, grasshoppers, and earwigs, together with white ants, dragon-flies, and may-flies, and numerous forms of beetles and bugs. But neither moths nor butterflies are certainly known to occur in Jurassic strata. Brachiopods have ceased to be dominant forms, but are still individually numerous—the most important genera being *Terebratula* (figs. 245, 248) and *Rhynchonella* (figs. 243, 250, 268). Two old Palæozoic forms, *Spirifera* (fig. 244) and *Leptæna*, make their final appearance in the Lias. The mollusca present many forms which are not known in Palæozoic strata. Among lamellibranchs the most conspicuous genera are the oysters, *Ostrea* (figs. 258, 267, 281), *Gryphæa* (figs. 246, 262, 281), and *Exogyra* (fig. 274); and *Trigonia* (figs. 253, 273), and *Pholadomya* (figs. 251, 266). Other forms commonly met with are *Lima*, *Pecten*, *Cardium*, *Lucina*, etc. (figs. 247, 270, 271, 272, 275). Fresh-water bivalves (*Cyrena*, *Unio*, figs. 280, 282) occur in the Purbeck beds. Gasteropods are fairly numerous—the most important forms being *Chemnitzia*, *Natica*, and *Cerithium* (figs. 265, 277, 278)—and the whole group, comprising representatives of the whelks, spindle-shells, spider-shells, etc., of existing seas, has a somewhat modern aspect. The earliest fresh-water univalves (*Paludina*, *Planorbis*, etc.) appear now. Amongst the carnivorous marine forms may be mentioned *Purpur-*

231. Hybodus reticulatus.

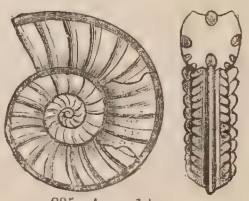
232. Acrodus nobilis.

234. Extracrinus Briareus.



233. Ammonites Bucklandi.

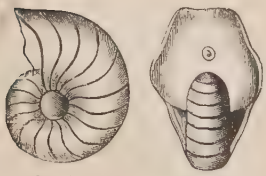
238. Belemnites elongatus.



235. Am. obtusus.

237. Ammonites margaritatus. *m.*

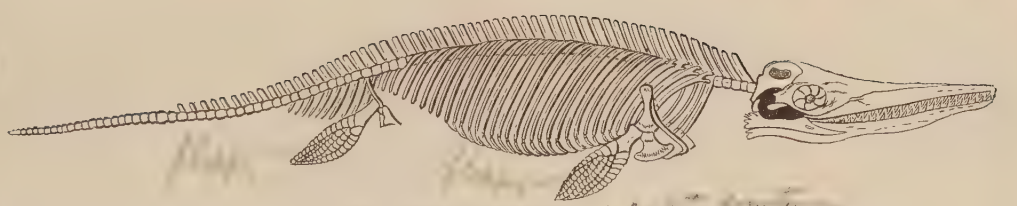
236. Am. serpentinus. *u.*



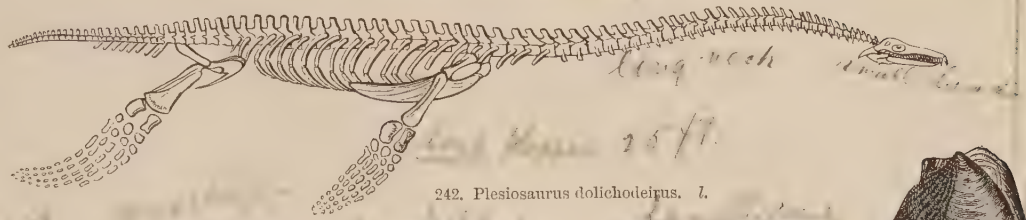
239. Nautilus truncatus.

240. Nautilus striatus.

Figs. 231 to 240.—FOSSILS FROM THE LIAS.
m, Marlstone (Middle Lias). *u*, Upper Lias; all the rest Lower Lias.

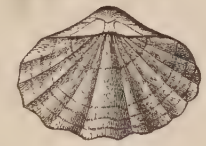


241. Ichthyosaurus communis. *l.*

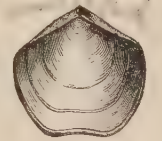


242. Plesiosaurus dolichodeirus. *l.*

243. Rhynchonella tetrahedra. *m.*



244. Spiriferina Walcotti. *l.*



245. Waldheimia numismalis. *l.*

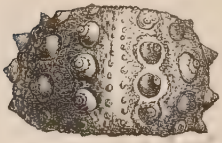
246. Gryphæa incurva. *l.*

247. Lima gigantea. *l.*

Figs. 241 to 247.—FOSSILS FROM THE LIAS.

l, Lower; *m*, Middle; *u*, Upper.

248. Terebratula perovalis.

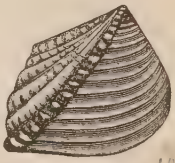


249. Acrosalenia hemicidaroides.

250. Rhynchonella spinosa.

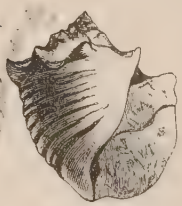
251. Pholadomya fidicula.

252. Nautilus sinuatus.



253. Trigonia costata.

254. Ammonites macrocephalus.



255. Purpuroidea Morrisea.

256. Am. Lumphriesianus.

257. Am. discus.

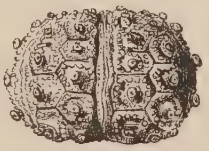
258. Ostrea flabelloides.

259. Am. Parkinsoni.

Figs. 248 to 259.—FOSSILS FROM THE LOWER OOLITES.

oidea (fig. 255), a common shell in the Great Oolite. But the most characteristic molluscs of Jurassic times are the cephalopods—both tetrabranchiate and dibranchiate types. Amongst the former we no longer meet with *Orthoceras* and *Goniatites*, but *Nautilus* (figs. 239, 240, 252) is still prominent. By far the most abundant forms, however, were Ammonites, of which more than 300 species are known. Many of the Jurassic ammonites are restricted in their range to particular beds; this is specially the case with the Lias,

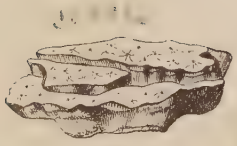
260. Ammonites Jason.



261. Cidaris florigemma.

262. Gryphæa dilatata.

263. Belemnites hastatus.



264. Isastræa explanata.

265. Chemnitzia heddingtonensis.

266. Pholadomya æqualis.

Figs. 260 to 266.—FOSSILS FROM THE MIDDLE OOLITES.

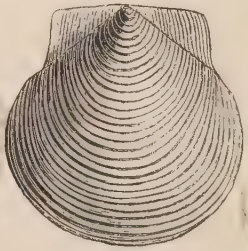
which has been divided into a series of zones, each of which is characterised by the presence of distinctive ammonites. Some of the more prominent species are given in the accompanying figures (figs. 233, 235, 236, 237, 254, 256, 257, 259, 260, 276). The dibranchiate cephalopods were hardly less numerous than the tetrabranchiate forms, and are represented chiefly by the internal shells or bones of cuttle-fishes. Occasionally the parrot-like "beak" or even the "ink-bag" is preserved. The great majority of these

267. Ostrea deltoidea.

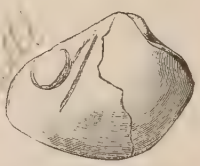
268. Rhynchonella inconstans.

269. Mantellia nidiformis.

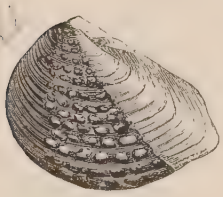
270. Cardium striatulum.



271. Pecten lamellosus.

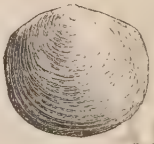


272. Cardium dissimile.



273. Trigonia gibbosa.

274. Exogyra virgula.



275. Lucina portlandica.

276. Ammonites biplex.

277. Natica elegans.

278. Cerithium portlandicum.

Figs. 267 to 278.—FOSSILS FROM THE UPPER OOLITES.
(Fig. 269 is from the Purbeck beds.)

remains belong to the genus *Belemnites* (figs. 238, 263). The ancient cuttle-fishes must have swarmed in Jurassic waters, for some beds are actually crammed with their internal bones.

Among fishes we find placoids and ganoids, which last have usually homocercal tails. Cestracionts are represented by fin-spines and teeth (*Hybodus*, fig. 231, *Acrodus*, fig. 232). But the most important vertebrates are reptiles, which flourished in extraordinary abundance during Jurassic times. Chelonians or turtles, lacertilians or lizards, and crocodiles (*Teleosaurus*) are all represented. But the most characteristic reptiles were the huge sea-saurians *Ichthyosaurus* (fig. 241), *Plesiosaurus* (fig. 242), and *Pliosaurus*. The ichthyosaurs were very large fish-like reptiles, sometimes attaining a length of over 20 feet. The head, joined to the body with no conspicuous neck, was long, and furnished with conical striated teeth, and the eyes, protected by a ring of bony plates, were of extraordinary size. These animals were provided with two pairs of flippers resembling the swimming-paddles of the whale. The plesiosaur had a long tapering snake-like neck which supported a relatively small head. The body was short, and furnished with

279. Physa Bristovii.

280. Unio compressus.

281. Ostrea distorta.

282. Cyrena media.

Figs. 279 to 282.—FOSSILS FROM THE PURBECK BEDS.

comparatively longer swimming-paddles than the ichthyosaur. One species was not less than 25 feet in length. The pliosaur was allied to the plesiosaur; it had, however, a short neck which supported an enormous head. The numerous coprolites, or fossil droppings of all these reptiles, charged as they are with the scales, etc., of ganoid fishes, prove them to have been carnivorous. Another remarkable group of Jurassic reptiles were the winged saurians (Pterosaurs). Amongst these the most characteristic was *Pterodactylus*. This animal attained no great size (a foot or more in length; the spread of the wings being some three feet or so). Most of the bones were hollow like those of birds, but the skin, teeth, and claws were reptilian. The outer finger of the forearm was greatly elongated, and between this long finger the side of the body and the hind limb stretched the membranous wing. *Dimorphodon* is a pterosaur closely related to *Pterodactylus*, but while

the latter had a short, the other had a long tail. *Rhamphorhynchus* also had a long tail with a steering membrane. Like the preceding forms it was toothed, but seems to have been provided with a horny beak. The lands of the Jurassic period were tenanted by dinosaurs, some of which attained a very great size. These creatures had two pairs of limbs—the hinder legs being, in some cases, much the stronger—from which it is inferred that certain forms had the power of walking on their hind-legs. In this and other respects (as in the structure of their skeleton) they seem to have affinities with the great wingless birds (ostrich and cassowary). Amongst European Jurassic dinosaurs may be mentioned *Cetiosaurus*, a vegetable-feeder, progressing on four feet, and reaching a length from snout to tip of tail of 45 feet, and the carnivorous *Megalosaurus*, probably 25 feet long, which had the power of walking on its hind-legs. But these large dinosaurs were greatly surpassed in size by those which have left their remains in the Jurassic of North America. Conspicuous amongst these is *Atlantosaurus*, which Professor Marsh, judging from the size of the bones, thinks must have attained a length of about 100 feet, with a height of at least 30 feet. From the lithographic stone of Solenhofen, in Bavaria (Upper Jurassic), come the remains of the oldest known bird (*Archæopteryx*), which had certain reptilian characteristics. It had three free claws belonging to the wing, and a lizard-like tail, composed of twenty-one to twenty-three biconcave vertebræ, each of which supported a pair of quill feathers; and its jaws were furnished with teeth. The bird was about the size of a rook.

The Purbeck beds and the Stonesfield Slate (Great Oolite) have yielded mammalian remains, chiefly jaws and a few detached bones. The animals which these represent were most probably small marsupials, some of them feeding on insects and others on vegetables (*Phascolotherium*, *Stereognathus*, *Spalacotherium*, *Plagiaulax*).

Physical Conditions.—During the Jurassic period the area now occupied in Britain and Ireland by the older rocks appears to have been for the most part dry land. The sea overflowed the north-east corner of Ireland and passed up the west coast of Scotland over the site of what is now the island of Skye, and it seems to have extended along the east coast also, covering a limited area in Sutherland. The mountains of Cumberland and Westmoreland, the Pennine chain, Wales, the heights of Devon and Cornwall, and a ridge of Palæozoic rocks which underlies London were the chief land areas in South Britain, so that nearly all England was under water in the earlier stages of the Jurassic period. The same sea overflowed extensive areas of what is now the European continent.

The older rocks in the north-west and north-east of France, and the Central Plateau of the same country, formed dry land—all the rest was submerged. In like manner the sea covered wide regions in the east of Spain. In Middle Europe it overflowed nearly all the low grounds of North Germany and extended far east into the heart of Russia. It occupied the site of the Jura Mountains and passed eastward into Bohemia, while on the south side of the Alps it spread over a large part of Italy, extending eastwards so as to submerge a broad region in Austro-Hungary and the Turkish provinces. Thus the northern latitudes of Europe continued to be the chief land-area; what are now the central and southern portions of the continent being a great archipelago in which appeared numerous islands, large and small. Where the waters of this sea in Central Europe were clear, coral reefs abounded—some of which appear to have circled round the old shore-lands like the fringing- and barrier-reefs of existing seas, while others may have been atolls, and some it would seem formed islets and were clothed with the vegetation peculiar to the period—chiefly cycads.

In the English area one of the most striking features of the Oolitic formations are the petrological changes which they undergo when we follow them from south to north. Thus in the south we have in the Inferior Oolites a series of purely marine deposits, betokening the presence there of a wide but apparently shallow sea. But as we trace these strata northwards they begin, as in Northamptonshire, to contain estuarine and fresh-water beds, while still farther north in Yorkshire the whole character of the series changes, and we have a succession of sandstones and shales with intercalated coal-seams resting on their underclays. Here, then, we have evidence to show that the chief land-area lay towards the north—from which large rivers descended bringing with them much sandy and argillaceous sediment. With such materials the shallow estuaries became silted up, while a thick growth of vegetation covered the low mud-banks through which the rivers flowed.

The Jurassic strata, attaining as they do a thickness of several thousand feet, point to a very considerable subsidence. The movement, however, was not continuous, but ever and anon interrupted by pauses. This, according to Philips, is indicated by the remarkable alternations of argillaceous, arenaceous, and calcareous strata, which are so marked a feature of the system in England. Taken as a whole, the Jurassic strata appear to have been laid down in a comparatively shallow sea, in which the conditions were extremely favourable to marine life, and to the preservation of organic remains.

After the deposition of the Portland beds of the Upper Oolite the widespread Jurassic sea which had covered so large a part of England disappeared, and dry land took its place. Thus, the fresh-water Purbeck beds, with their ancient terrestrial surfaces (dirt-beds) rest on a denuded surface of the preceding group. The bottom strata of the Purbeckian are of fresh-water origin and would appear to have been laid down at the mouth of a river which probably flowed from the north. These strata are overlaid by marine beds showing that the sea for some time gained upon the land, but eventually fresh-water conditions again prevailed, for the marine strata are in their turn covered by beds of fresh-water origin. Similar indications of a more or less abrupt change from sea to fresh-water is afforded by the Jurassic in various parts of Central Europe, as in Hanover, the Jura, and Westphalia.

The climatic conditions of the Jurassic period over a vast portion of the earth's surface appear to have been extremely genial. The seas teemed with forms of life whose nearest living representatives are now met with chiefly in the warmer oceans. Thus coral-builders flourished in latitudes which are now some 3000 miles north of their present limits, while cuttle-fishes and ammonites, and, more remarkable still, ichthyosaurs and teleosaurs lived far within the Arctic Circle. Nevertheless it would seem that the northern Jurassic seas were not tenanted by so abundant and varied a fauna as characterised the corallian seas of Central Europe. In the Scottish Jurassic some coarse boulder-beds occur which point to the existence of contemporaneous glaciers in some of the mountain-valleys of the Northern Highlands.

III.—CRETACEOUS.

The Cretaceous system of the British area is composed of two series—upper and lower—the latter being partly marine and partly of fresh-water origin while the former is exclusively marine. The Jurassic in England is flanked along its eastern borders by a great belt of Cretaceous, underneath which it dips. Cretaceous strata form the Yorkshire Wolds, cover large areas in Norfolk, Suffolk, and Hertford, compose the Chiltern Hills, Salisbury Plain, the North and South Downs, and occupy the south part of the Isle of Wight. The following is the succession met with :—

		Feet.
Upper Cretaceous	Upper Chalk	600
	Middle Chalk	200
	Lower Chalk and Chalk Marl .	450

			Feet.
Upper Cretaceous	Chloritic Marl, Upper Greensand	. . .	250
	Gault		200
Lower Cretaceous (Neocomian)	Lower Greensand . . .		550
	Weald Clay, 1000 Hastings Sands, 850	Wealden .	1850

The *Hastings Sands* and *Wealden Clay* are composed almost entirely of fresh-water strata—the former consisting of a series of sands and clays with lenticular beds of limestone—the latter being chiefly clay, with occasional thin bands of shelly limestone (Sussex marble). Here and there in the Weald Clay occur thin layers with marine shells, but with such exceptions the fossils of the Wealden are chiefly fresh-water shells, ostracods, and fishes. Land-plants also occur, and numerous remains of great reptiles. The Wealden beds are confined to the south of England (occupying the district known as the Weald of Kent, Surrey, and Sussex). In Yorkshire the strata which occur on the same horizon are of marine formation (Speeton Clay).

The *Lower Greensand*, overlying the Wealden, consists of irregular alternations of clays, sands, and calcareous grits, generally dark brown or red in colour, but sometimes tinged green from the presence of grains of glauconite. The beds are all marine, and are believed to be on the same geological horizon as the upper part of the Speeton clay of Yorkshire.

The *Gault*, forming the basement group of the Upper Cretaceous, reposes on the Lower Greensand when that is present. It is a tough blue clay, more or less abundantly charged with marine organic remains.

The *Upper Greensand* consists principally of sands, sometimes hardened into sandstone—all shallow-water deposits of marine origin. The group is of very variable thickness, and seems to be confined to the south of England. It is overlaid by the *Chloritic Marl*, a thin bed of chalky marl, containing glauconitic grains and phosphatic nodules, which is confined, like the Upper Greensand, to the southern districts. In Bedfordshire and Cambridgeshire the Chloritic Marl is represented by a thin layer charged with numerous phosphatic nodules and many erratics. The *Chalk Marl* is an argillaceous chalk, resting conformably upon the Chloritic Marl when that is present, and passing up conformably into the Lower Chalk.

The *Lower* or *Grey Chalk* is a greyish white chalk, well-developed in the south-east of England.

The *Middle Chalk* is a pure white chalk, containing in its upper portions layers of flint nodules. A band of hard yellowish

limestone, called the "chalk rock," forms the topmost layer of the division.

The *Upper Chalk* is a thick massive white chalk characterised by the presence of numerous layers of nodules and occasional tabular sheets of flint, arranged in the line of bedding. Here and there small pebbles are met with in the Chalk, but they are very rare. Near Croydon a group of erratics occurred, the largest of which was a fragment of syenite weighing about forty pounds. It was accompanied by pebbles and sand.

Although all these divisions appear to form a conformable series yet there is evidence to show that here and there breaks in the succession occur. Many of these are probably local, but others may be more general. Such a break would seem, according to Mr. Jukes-Browne, to occur between the Grey Chalk of Cambridgeshire and the overlying Middle Chalk—a break marked by unconformity and by the abrupt disappearance of many species and their replacement by new forms. The remarkable purity of the white Chalk points to accumulation in clear water. The rock is largely composed of the shells of foraminifera and the débris of other marine organisms—molluscs, urchins, etc. It would seem, however, that these massive white limestones were probably not accumulated continuously. Now and again distinct platforms of hardened and corroded chalk occur, pointing, as some geologists think, to epochs of emergence and erosion.

Cretaceous strata, overlaid by Tertiary volcanic rocks, occur in the north of Ireland (Antrim), and in the west of Scotland (Mull and Morven).

Foreign Cretaceous.—The Cretaceous strata continue under the Channel and the North Sea, and re-appear on the opposite coasts of the Continent, forming a broad basin in the north of France, and extending eastwards from Belgium, Holland, Denmark, and the south of Sweden through the vast plains of Germany, Poland, and Russia to the south end of the Urals. Over very wide areas, however, they lie concealed beneath younger formations. The southern limits of this great belt are traced from Westphalia eastwards along the flanks of the Harz, the Riesengebirge, and the Carpathians. The system is also extensively developed in the south of Europe—covering considerable areas in the south-west and south of France and the east of Spain. From the Rhone valley it strikes along the northern flanks of the Alps in the form of narrow belts or zones, through Bavaria and the Tyrol into Austria; and appears on the south side of the same great range and along the ridge of the Apennines. It is likewise well developed in Istria, Dalmatia, Greece, Bulgaria, and along the southern margin of the

Black Sea. To the same great southern area belong the Cretaceous strata of Algeria and Palestine.

The system, as developed on the Continent, has been subdivided by the French geologists (whose nomenclature is now generally adopted), as follows :—

Continental Cretaceous.	Equivalent English Strata.
Danian	Wanting.
Senonian	Upper Chalk.
Turonian	Middle Chalk.
Cenomanian	Lower Chalk and Chalk Marl. Chloritic Marl. Upper Greensand.
Gault or Albian	Gault.
Neocomian	Lower Greensand. Wealden.

It will be observed that the upper division of the Continental series is wanting in England. The Danian is represented by patches of soft yellowish limestones which occur in the north of the Paris basin, in the valley of the Meuse at Maestricht, and at Faxœ in Seeland (Denmark). These beds lie unconformably upon the Senonian and are charged with fossils, some of which are common to the underlying strata, while others consist of Tertiary forms. There is clearly a break in the succession, therefore, between the Senonian and Danian. The Cretaceous strata of the Paris basin present much the same character as those of England, but when the system is followed east into Germany it undergoes a great change. The soft powdery white chalks of the Anglo-French area are gradually replaced by earthy limestones, shales, sandstones, etc. ; and the whole appearance of the strata differs so strongly from that of their equivalents in Western Europe, that it is only by means of their fossils that they could be identified. Thus in Westphalia the Upper Chalk is represented chiefly by arenaceous deposits ; while in Saxony and Bohemia similar sedimentary accumulations constitute nearly the whole of the Cretaceous formations—the lower beds of the Cenomanian in those countries containing shales and clays, crowded with the relics of a terrestrial flora.

The Cretaceous of Southern Europe differs considerably from that of the northern province ; its most distinguishing feature being the enormous development of massive marine limestone (Hippurite limestone), which occurs throughout the Mediterranean region, ranging through Asia Minor into Persia.

In North America the system is well represented, appearing on the Atlantic border at intervals between New Jersey and South Carolina, and covering wide regions in the Gulf States, whence it sweeps up the Mississippi valley to the Ohio. It has a very extensive development in the Western States and Territories—Texas, Dakotah, Wyoming, Utah, and Colorado ; and occurs also in the coast-ranges west of the Sierra Nevada. Farther north it has been traced over a very considerable area in the valleys of the Saskatchewan and the Assiniboine. Still farther north it has been met with on the borders of the Arctic Ocean, at the mouth of the Mackenzie River, and in North Greenland. In Texas the system is largely composed of firm compact limestones containing hippurites and foraminifera. In the regions to the north, however, arenaceous and argillaceous strata predominate. They attain a thickness of more than 11,000 feet in Utah and Wyoming, and show numerous alternations of marine, fluviatile, and terrestrial accumulations. The highest group of the series (Lignitic group) contains numerous coal-seams, the plants in which are of Tertiary types, while the mollusca in the associated aqueous strata are distinctly Cretaceous forms.

Cretaceous strata occur in India, and are associated in the Deccan with basalt-rocks, which reach from 4000 to 6000 feet in thickness, and cover an area of 200,000 square miles. In New Zealand and Australia Cretaceous rocks are also well developed.

283. Cypridea valdensis.

284. Paludina fluviorum.

Figs. 283, 284.—FOSSILS FROM THE WEALDEN.

Life of the Period.—As the Cretaceous rocks of Britain are mostly of marine origin—many of them deposited at some distance from the land—we need feel no surprise that land-plants are of uncommon occurrence in British Cretaceous strata. In the Lower Cretaceous they consist principally of ferns, cycads, and conifers—a flora of the same character as that of the Jurassic period. In the more purely marine Upper Cretaceous of our area plants rarely occur, but in the equivalent strata of Germany numerous plants have been detected. Amongst these are many dicotyledons (the earliest appearance of that great class), such as species of maple, willow, alder, oak, bog-myrtle, walnut, beech, laurel, magnolia, etc. Along with these occur a number of proteaceous plants, some of

which are referred to living genera, belonging chiefly to Australia. A similar admixture of modern forms is met with in the Cretaceous of Greenland and North America.

The Protozoa played a very important part in the Cretaceous seas—the white chalk and other limestones being often largely composed of the minute shells of foraminifera—the most prominent forms being *Globigerina* (fig. 317), *Rotalia*, and *Textularia*, which still swarm in the ooze of the Atlantic. Sponges, of which many forms are known, two of the commoner being *Siphonia* (fig. 306) and *Ventriculites*, were numerous. Corals were much less common than in the preceding period, and crinoids are poorly represented; but echinoids (urchins) abounded, such as *Echinocorys* (fig. 309), *Micraster* (fig. 307), *Salenia* (fig. 304), *Galerites* (fig. 311). Star-fishes (amongst them the pentagonal-shaped cushion-star, *Goniaster*, fig. 308) also occur. The Crustacea are not particularly noteworthy; the most abundant forms being fresh-water ostracods, such as *Cypridea* (fig. 283), which is common in the Wealden beds. Crabs and lobsters (fig. 289) are the more prominent forms. Sea-mats and sea-mosses (Polyzoa) are fairly plentiful; and so also are certain genera of brachiopods, such as *Terebratula* (figs. 291, 302, 315) and *Rhynchonella* (fig. 305). Lamellibranchs are exceedingly abundant; and some are very characteristic of Cretaceous deposits, such as *Inoceramus* (figs. 295, 312) and the *Hippuritidæ*, which last are not met with in any other system. Other common bivalves are *Ostrea*, *Exogyra*, *Spondylus* (fig. 316), *Lima* (fig. 298), *Pecten* (figs. 293, 303, 313), *Perna* (fig. 292), *Nucula* (fig. 299), *Plicatula* (fig. 300), etc. Amongst univalves (which are not so abundant as lamellibranchs), may be mentioned *Natica* (fig. 296), *Pleurotomaria*, *Cerithium*, *Aporrhais* (fig. 297). It is noteworthy that in the youngest Cretaceous rocks (Danian) many carnivorous gasteropods occur, including a number of existing genera such as *Voluta*, *Cypræa*, *Strombus*, *Mitra*, etc. All the molluscs mentioned are of course marine. In the Wealden beds occur fresh-water shells such as *Unio*, *Cyrena*, *Paludina* (fig. 284), and also land-shells. Cephalopods are among the most abundant and characteristic fossils met with in the Cretaceous of England and Middle Europe. The ancient genus *Nautilus* appears together with some old forms of the family of the *Ammonitidæ* such as the type genus itself, *Ammonites* (figs. 286, 287, 291), and *Ancyloceras* (fig. 285). Associated with these are many new and beautiful forms, as *Turrilites* (fig. 310), *Crioceras* (fig. 288), *Scaphites* (fig. 314), *Hamites* (fig. 294), *Ptychoceras*, *Toxoceras*, *Baculites*. The *Ammonitidæ* did not survive the Cretaceous period. The same was the case with the dibranchiate *Belemnitidæ*, which are characteristically represented by *Belemnitella* of the Upper Chalk.

285. Ancyloceras gigas.

286. Ammonites Noricus.

287. Am. Deshayesi.

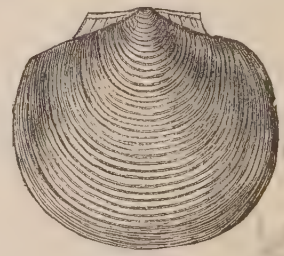
288. Crioceras Duvalli.

289. Meyeria magna.

290. Terebratula sella.

291. Am. speetonensis.

292. Perna Mulleti.

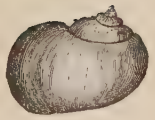


293. Pecten cinctus.

Figs. 285 to 293.—FOSSILS FROM THE LOWER GREENSAND.
(Figs. 286, 288, 291, 293, are from the Speeton Clay.)

294. Hamites intermedius.

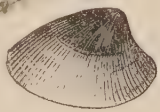
295. Inoceramus sulcatus.



296. Natica gaultina.

297. Aporrhais carinata.

298. Lima parallela.



299. Nucula pectinata.

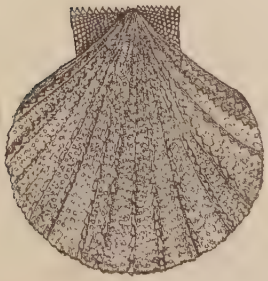
300. Plicatula pectinoides.

Figs. 294 to 300.—FOSSILS FROM THE GAULT.

301. Nautilus pseudo-elegans.

302. Terebratula biplicata.

304. Salenia personata.

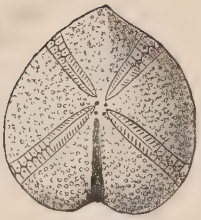


303. Pecten asper.

305. Rhynchonella latissima.

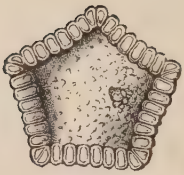
306. Siphonia pyriformis.

Figs. 301 to 306.—FOSSILS FROM THE UPPER GREENSAND.

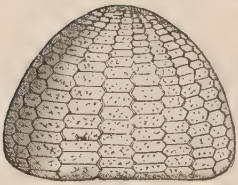


307. Micraster cor-anguinum.

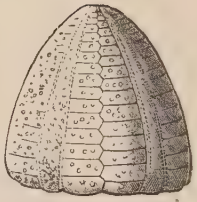
310. Turrilites costatus.



308. Goniaster Coombei.

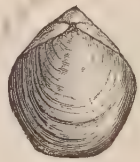


309. Echinocorys ovatus.

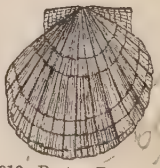


311. Galerites albo-galerus.

312. Inoceramus mytiloides.



315. Terebratula carnea.



313. Pecten Beaveri.

314. Scaphites æqualis.

317. Globigerina bulloides.

316. Spondylus spinosa.

Figs. 307 to 317.—FOSSILS FROM THE CHALK.

Among fishes we find ganoids, chimæroids (*Edapodon*), and representatives of the sharks and rays (*Otodus*, *Lamna*, *Ptychodus*). Teleost fishes (which include most living genera), make their first appearance in Cretaceous strata; and represent the modern groups of salmon, perch, herring, etc.

Reptilian remains occur plentifully, but are hardly so common as in the Jurassic strata. Among the forms some date back to the preceding period, while others are new. Thus, in the European Cretaceous we find representatives of the great swimming reptiles of the Jurassic—ichthyosaurs and plesiosaurs. Pterosaurs are likewise present, several species of pterodactyl being known, some of which seem to have attained a much larger size than their Jurassic predecessors. Amongst dinosaurs, *Ceteosaurus* and *Megalosaurus* also survived, and were associated with several new forms, one of the most notable being the huge herbivorous *Iguanodon* of the Wealden. Another conspicuous reptile of the European Cretaceous is the great serpent-like *Mosasaurus*, which was provided with two pairs of paddles, and was doubtless essentially aquatic. The lizards are represented by several small forms, and a few chelonians likewise have been met with, none of them differing widely from existing types. In the Wealden beds remains of true crocodiles and a tooth of some small mammal have been obtained, while from the "Cambridge Greensand" (=Chloritic Marl) have come bones of what appear to have been swimming or wading birds.

The American Cretaceous has yielded a large series of reptilian remains, some of which betoken animals allied to European Cretaceous forms. Amongst these were huge dinosaurs such as *Hadrosaurus*, about 28 feet long, and *Lælaps*, not much less in size—the former resembling *Iguanodon*, and the latter *Megalosaurus*. *Mosasaurus* is represented by upwards of forty species, one of which attained a length of 75 to 80 feet. Pterosaurs are likewise present, one of which had a spread of wings of 25 feet. They had no teeth, like the European forms, but their jaws were probably sheathed with horn, as in the case of birds. Of American swimming reptiles one of the most remarkable is *Discosaurus*, the body of which was 40 feet long. It had a swan-like neck of over sixty vertebræ, measuring 22 feet in length, which supported a slim arrow-shaped head. Besides these strange forms the American Cretaceous vertebrate fauna included true crocodiles and turtles, also a number of birds, some of which are related to the modern group of waders, while others differ from all birds in possessing small pointed teeth, which in one form (*Ichthyornis*) were sunk in distinct sockets, and in another type (*Hesperornis*) were implanted in a deep continuous groove, as in ichthyosaurus. In *Ichthyornis*

the vertebræ are biconcave. It was a small bird about the size of a pigeon, had relatively powerful wings, and was probably aquatic, living upon fishes. *Hesperornis* was a large diving-bird (measuring six feet from the bill to the tip of the tail), its wings were rudimentary, its legs powerful, and its feet well adapted for rapid progression in water. The tail was broad, could move up and down, and was probably used as a rudder or swimming-paddle.

Physical Conditions.—No break separates the Jurassic from the Cretaceous period. In the south of England the Purbeck beds pass up into and are continuous with the Wealden series. So far then as our area is concerned the Cretaceous period opens at a time when wide regions of the Jurassic sea-bottom had been converted into dry land. The sea overflowed some part of eastern England, but, so far as we know, the greater portion of the British and Irish area was dry land. Over the south-east of England lay the estuary of a great river which probably flowed from the north, and in this estuary the Wealden deposits were gradually accumulated. These deposits have been met with also in the Boulonnais, and Ramsay has estimated the area occupied by the ancient delta as not less than 20,000 square miles. But as the deposits have doubtless been greatly removed by denudation, he thinks that 30,000 square miles would be a moderate estimate for the original extent of the delta. While the Wealden beds were being accumulated in our area a similar formation was taking place in North-west Germany—for Wealden beds have been followed at intervals from Helmstädt in Brunswick to Bentheim on the borders of Holland. At the beginning of Cretaceous times, then, Northern and Middle Europe were mainly in the condition of dry land. The sea, however, occupied the basin of the North Sea, extending into Eastern England on the one side and spreading over the Low Countries into Hanover, and it also covered a considerable area in the north of France. Into this ancient sea flowed the great rivers from the north. The lands drained by them were clothed with ferns, cycads, and conifers, and haunted by great dinosaurs, while turtles and crocodiles frequented the waters, where also ganoids and sharks abounded. But while land predominated in Middle and Northern Europe, an open sea overflowed vast areas in the south.

The deposition of the Wealden beds and the accumulation of the equivalent marine strata (Lower and Middle Neocomian) must necessarily have taken a long time. While these Lower Cretaceous groups were being laid down a gradual subsidence ensued, the shores of the Cretaceous land retreated, the great deltas became submerged, and by and by a wide sea covered most of what are now the low grounds of the British area, and passing eastwards eventu-

ally overwhelmed vast regions in Middle Europe up to the slopes of the Ural Mountains. The depression, however, would seem to have been greatest in the western areas, where in the deeper clear waters foraminifera and other marine organisms so abounded as to give rise to massive accumulations of the white calcareous rock called chalk. Farther east, in what are now Saxony, Bohemia, etc., the sea was shallower, and gradually became silted up with arenaceous deposits. In the Mediterranean basin the calcareous deposits, contemporaneous with those of Middle Europe, indicate throughout an open sea, which covered large portions of Eastern Spain and Southern France, overflowed the site of the Jura Mountains, covered most of the Alpine area, the Italian peninsula, the eastern borders of the Adriatic, and Greece. In short, there is good reason for believing that the Cretaceous Mediterranean was not only much broader than the present sea, but that it passed into Asia, overwhelming vast regions there, and communicated with the Indian Ocean.

With regard to climatic conditions all we can say is that as yet there is no evidence of such strongly contrasted zones as characterise the present. Ferns, cycads, and conifers flourished in North Greenland, and the waters of the Arctic Sea were tenanted by cuttle-fishes, ammonites, and huge reptiles, such as ichthyosaurus, from which we may infer that the climate of lower latitudes could not but have been warm. But the occurrence of erratics in the White Chalk of Croydon and in the "Cambridge Greensand" shows that ice sometimes, at all events, floated in the Cretaceous seas.

GENERAL CHARACTER OF MESOZOIC FLORAS AND FAUNAS.

The life of the Mesozoic era is strongly contrasted in many respects with that of Palæozoic times. In place of calamites, sigillariæ, and lepidodendra, we have as prevalent forms, up to near the close of the Cretaceous period, arborescent and herbaceous ferns, conifers, and cycads, the last attaining a great development and reaching their culmination; while in late Cretaceous times appear the earliest representatives of the great class of Angiosperms. The Palæozoic group of rugose corals has become practically extinct, only one member of the group (*Holocystis*) occurring in Mesozoic strata. The corals which were plentiful in some Mesozoic seas consisted almost exclusively of modern types. Echinoids and star-fishes abounded, the former being very predominant in the waters of Cretaceous times; but crinoids, which were so prevalent in Palæo-

zoic seas, were now much reduced in numbers. Some of the higher grades of the Crustacea (true crabs), which are hardly known in Palæozoic strata,[1] were plentiful in Mesozoic times, and the same was the case with the insects. Brachiopods are no longer dominant forms; and amongst the molluscs the cephalopods take the lead. Both tetrabranchiate and dibranchiate divisions reach their maximum development, the former represented by swarms of *Ammonitidæ*, and the latter, which makes its first appearance now, by prodigious numbers of *Belemnitidæ*. The Palæozoic types of *Orthoceras* and *Cyrtoceras* died out in early Mesozoic times, the only ancient form that persisted being *Nautilus*, which survives in existing seas. Among gasteropods and lamellibranchs, which are well represented, were a number of modern genera, and these increased towards the close of the Cretaceous period; and, as we shall afterwards see, this increase was continued in Tertiary times, both classes seeming to reach their maximum in the present. The ganoids (which culminated in the Old Red Sandstone period) are still numerous. But now most of them have homocercal or symmetrical tails. Chimæroids are represented, while true sharks and rays abounded, and teleosteans or bony fishes made their earliest appearance. The labyrinthodonts, which in Triassic times attained a great size, soon died out, making way for the advent of a prodigious reptilian fauna. So abundant are reptilian remains in Mesozoic strata that the age is often termed the "Age of Reptiles." There were enaliosaurs (swimming reptiles), pterosaurs (flying reptiles), mosasaurs (snake-like reptiles), dinosaurs, crocodiles, and chelonians. This reptilian life abounded all through the Mesozoic, but was specially rife in the Jurassic period. Birds were probably numerous, some of the forms being toothed, while others were of modern types. Mammals were still represented by only the inferior grade of marsupials. They were all of small size.

The Mesozoic animals afford many good examples of comprehensive or synthetic types. Thus, in *Archæopteryx* we see a true bird with reptilian teeth and a long lizard-like tail, while in the toothed birds of America we have true birds with similar teeth and the biconcave vertebræ of fishes. The reptilian pterodactyle, again, had the pneumatic bones of birds. In plesiosaur and ichthyosaur we have a combination of reptilian and piscine characteristics, while the lacertilian mosasaurs in some measure recall the serpents. Once more the dinosaurs have certain features which are now met with in widely separated types—as lizards, crocodiles, birds, and mammals.

[1] Apparently the only Palæozoic crab is the minute *Hemitrochiscus* of the Permian.

All these remarkable reptiles became extinct before the beginning of the Tertiary era. So it was with many characteristic Mesozoic molluscan families, such as *Ammonitidæ, Belemnitidæ*, and *Hippuritidæ*. Putting aside the lowly organised protozoa it may be said that hardly one Cretaceous species has been met with in Tertiary strata.

EVOLUTION OF CONTINENTAL AREAS IN MESOZOIC TIMES.

Amidst the many geographical changes which took place in the European area during the Mesozoic era a wide land-surface appears to have persisted in the north, just as was the case in Palæozoic times. The highest grounds were the Urals and the uplands of Scandinavia and Britain. In Middle Europe the Pyrenees and the Alps were as yet inconsiderable heights, the loftiest lands being those of the Harz, the Riesengebirge, and other regions of Archæan and Palæozoic rocks. The lower parts of England and the great plains of Central Europe were sometimes submerged in the waters of a more or less continuous sea, but ever and anon elevation ensued, wide areas became dry land, and the sea was divided, as it were, into a series of great inland lakes. In the south of Europe a Mediterranean sea would appear to have persisted all through the Mesozoic era,—a Mediterranean of considerably greater extent, however, than the present. Thus we see that the main features of our continent were already broadly sketched out before the close of the Cretaceous period. The continental area then, as now, consisted of a wide belt of high ground in the north, extending roughly from west to east; south of this a vast stretch of low grounds, sweeping from west to east up to the foot of the Urals, and bounded on the south by an irregular zone of elevated land, having approximately the same trend; still farther south the maritime tracts of the Mediterranean basin. During periods of depression the low grounds of Central Europe were invaded by the sea, and the Mediterranean at the same time extended north over many regions, which are now land. It is in those two low-lying tracts therefore, and the countries immediately adjoining them, that the Mesozoic strata of Europe are chiefly developed. A general movement of upheaval supervened at the close of the Cretaceous period, and the sea, which, during that period covered such wide areas in Middle Europe, had largely disappeared from those regions before the beginning of Tertiary times.

North America during the Mesozoic period appears to have been

mostly land, the chief submerged area extending along what is now its Western Interior or Rocky Mountain region.

The organic remains of Mesozoic times speak to us only of genial climatic conditions, which prevailed from what are now temperate latitudes up to polar regions. But although we have no evidence of strongly contrasted zones such as now obtain, nevertheless, the Mesozoic strata of Southern and Central Europe contain the relics of a more abundant and diversified fauna than are met with in more northern latitudes, which seems to indicate that in those times the climate of the latter was less genial than that of regions farther south. We have also the evidence of the morainic boulder-beds of the Scottish Jurassic and the erratics of the English Cretaceous to show that the climatic conditions did not forbid the existence of glaciers and floating ice.

CHAPTER XXIV.

HISTORICAL GEOLOGY—TERTIARY OR CAINOZOIC SYSTEMS.

Eocene system: life; physical conditions—Oligocene: life; physical conditions—Miocene: life; physical conditions—Pliocene: life; physical conditions—General character of Cainozoic floras and faunas—Evolution of continental areas in Cainozoic times.

I.—EOCENE.

Reference has been made to the fact that not a few Palæozoic genera lived on into Mesozoic times, while a smaller number have persisted to the present day. In like manner we shall see that many Mesozoic genera survived into Cainozoic periods, and a not inconsiderable number still flourish in the living world. With species it is otherwise. Hardly one species of higher grade than the protozoa survived the close of the Cretaceous period. But when we reach the Tertiary formations we find that not only genera, but many species also, have come down to the present time. A few of these date from the earlier Cainozoic period, a still larger number from later stages, the percentage of living forms always increasing as we advance from older to younger strata. Now the original classification of the Tertiary deposits proposed by Lyell was based on the proportions of living species of molluscs which the strata contained. Those beds which contained the smallest number ($3\frac{1}{2}$ per cent) of existing species he termed *Eocene* (dawn of the recent); the deposits charged with a larger number than the Eocene, but *less* than one half (17 per cent) of the total number of shells present, were named *Miocene* (less recent); while *Pliocene* (more recent) was the term applied to strata in which *more* than half of the molluscs belonged to existing species. In the lower beds of the Pliocene the percentage ranged from 30 to 35, while in the upper beds it varied from 90 to 95. Lastly, deposits in which all the molluscs were existing species were termed *Pleistocene* (most recent). With necessary modifications this classification has maintained its place, but the names first suggested by an examination of the Euro-

pean Tertiary strata are now applied everywhere to rocks of that age, without reference to the precise percentage of living molluscan species they may chance to contain. Of late years a new group, *Oligocene* (few recent), has been introduced into the series. This has been done by separating an upper portion of the Eocene and uniting it with a lower part of the Miocene as one system. The Pleistocene forms now the lower stage of the succeeding Quaternary or Post-tertiary systems.

The Eocene system, as developed in England, occurs chiefly in two districts, called respectively the London and Hampshire basins. The strata probably at one time stretched continuously from the coast of Suffolk across the whole south-east part of England down to the coast of Dorset. But owing to subsequent subterranean action, accompanied and followed by great denudation, it has disappeared entirely from that wide tract that extends east from Hampshire through the Weald to the English Channel and the Straits of Dover. The system comprises three groups: Lower, Middle, and Upper Eocene, which are differently developed in the two basins. Grouping the strata of the London and Hampshire areas together we have the following succession:—

		Feet.
Upper Eocene	Headon Hill Sands, Barton Clay; Upper Bagshots	300
Middle „	Bracklesham beds; Middle Bagshot Sands	550
Lower „	Lower Bagshot Sands	125
	London clay and Bognor beds	up to 500
	Oldhaven beds	30
	Woolwich and Reading beds	90 to 140
	Thanet Sands	90

The *Thanet Sands* are a series of light-coloured, yellowish, and greenish sands. They are thickest in the Isle of Thanet, and are confined to the London basin = 90 feet. Fossils all marine.

The *Woolwich and Reading Series* or *Plastic Clay* consists of irregular beds of clays, loams, sands, and gravels, which vary much in character and thickness. The fossil organic remains are partly of marine and partly of fluviatile or estuarine origin. Some land-plants occur.

The *Oldhaven Beds* consist chiefly of flint shingle and gravel and sand, and occur only in the London basin. Their fossils are mostly marine, but estuarine forms are also present. A few land-plants occur.

The *London Clay* is a dark brown and bluish-grey stiff unctuous clay, with septarian nodules. In the Hampshire basin the corresponding strata (*Bognor Beds*) consist of dark blue clays and sands,

with occasional beds of argillaceous sandstones, and at the bottom a conglomerate. The fossils are chiefly marine; but many plant-remains and relics of terrestrial animals occur, especially in the upper portion of the series.

The *Lower and Middle Bagshot Sands* consist of yellow siliceous sands with occasional argillaceous beds, which in the London basin attain a thickness of 150 to 200 feet and more. In the Hampshire basin the "Lower Sands" are much thicker (660 feet in the Isle of Wight). The "Middle Sands" in the same basin are represented by the *Bracklesham Beds*, consisting of 100 feet of dark-coloured clays, marls, and white and green sands, with some lignites. The Lower Bagshot Sands are mostly unfossiliferous in both basins. In the London basin the "Middle Sands" contain a few marine organic remains, while the equivalent beds of the Hampshire basin (Bracklesham) are highly fossiliferous. At Bournemouth and Alum Bay many land-plants occur in the Middle Eocene.

The *Barton Clay*, consisting chiefly of greenish clay with layers of sand, is confined to the Hampshire basin. It abounds with marine organic remains. The *Upper Bagshot Sands* are a group of pale yellowish and white sands and clays.

Foreign Eocene.—Eocene deposits are well developed in the north of France, where they occupy a basin, in the centre of which is Paris. The chief divisions of the system in this basin are as follows:—

Upper Eocene	*Gyps Marin:* gypsum and marls with marine fossils. *Sables Moyens:* chiefly light-coloured siliceous sands, with plentiful marine molluscs; also a thin impure limestone with fresh-water shells.
Middle Eocene	*Calcaire grossier:* a series of sandy, marly, or glauconitic limestones. The lower beds are rich in nummulites and oysters; in the middle beds of the series occurs the Miliolite limestone, composed entirely of foraminifera. One of the commonest gasteropods of the Parisian basin is *Cerithium*, of which at least 150 species occur. The most famous fossils of the Calcaire grossier are *Palæotherium* and other pachyderms.
Lower Eocene	*Sables de Cuise:* a series of micaceous and glauconitic sands, with marine organisms. *Argile plastique*, and *Lignites du Soissonnais:* are the equivalents of the Woolwich and Reading series.

Lower Eocene —*continued*	*Sables de Bracheux:* consist of a lower group of marls and white sands, containing fresh-water shells; and an upper group of greyish sands charged with marine organisms. These groups are the representatives of the English Thanet Sands.

In Belgium the Eocene system is likewise well developed. At the bottom of the system occurs a thick marine limestone (Mons Limestone) which does not appear in the English and French series. The London Clay, which is very sparingly represented in the Paris basin, reappears in the Belgian area, where it is composed of a considerable thickness of clays and sands.

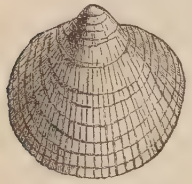
In Southern Europe the Eocene system differs very much in character from that of the Anglo-French and Belgian area. In place of more or less circumscribed basins of clays, sands, and other incoherent strata we are presented in the south of Europe with a calcareous formation comparable in thickness and extent to the great Hippurite Limestone of the Cretaceous system. This southern type of the Eocene is represented chiefly by a massive, compact, tough limestone, of a greyish, brownish, and sometimes yellowish or reddish colour, which is characterised by the presence of prodigious numbers of nummulites. In many places the limestone consists of little more than an aggregation of these foraminiferous shells. Here and there it becomes arenaceous, the sandstones being also thickly set with the same fossils. This remarkable formation attains a thickness of several thousand feet, and has been traced over a vast area. It appears on both sides of the Mediterranean basin, in Spain and in Morocco. It enters largely into the composition of the Apennines, the Alps, the Carpathians, and the Balkans; it extends through Greece, Egypt, and Asia Minor, and thence through Persia and the Himalaya to the coasts of China and Japan.

In the region of the Alps occurs a massive series of dark-coloured sandstones, shales, and argillaceous limestones, locally known as *Flysch*, the lower portions of which have been assigned to the Cretaceous, while the upper portions are believed to belong to the Eocene. The beds contain many fucoids (fucoidal sandstones). In Bavaria the Flysch is associated with nummulitic limestone; it contains many gigantic erratics of various crystalline rocks, none of which has been identified with any Alpine rock. They may have come from the Archæan masses of Bohemia to which they have the closest resemblance.

In North America the most important Eocene deposits are of

fresh-water formation, which occur chiefly in the Rocky Mountains and the plateaux lying west of that region. These strata bespeak the former presence of vast fresh-water lakes, and have yielded remains of many remarkable mammals. Marine deposits of the same age occur along the borders of the Atlantic, the Mexican Gulf, and the Pacific.

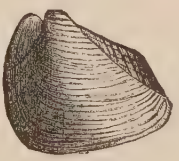
Life of the Period.[1]—The flora of the Eocene is tolerably well represented—most of the plants being referable to the Dicotyledons and the Monocotyledons. Among the more notable forms



318. Pectunculus terebratularis.

319. Cucullæa decussata.

320. Cardium Laytoni.



323. Pholadomya cuneata.

321. Aporrhais Sowerbyi.

322. Cyprina planata.

324. Corbula regulbiensis.

Figs. 318 to 324.—FOSSILS FROM THE THANET SANDS.

of the London Clay, are species of palm and screw-pine (*Nipa*); cypresses, which recall certain existing Tasmanian forms; and various proteaceous plants allied to living Australian genera. Besides these were species of custard-apple, gourd, melon, almond, oak, walnut, magnolia, etc. Amongst the plants of Middle Eocene time were species of the Australian proteaceous forms, gum-tree, nettle-tree, and banksia; fan-palms and screw-pines, aroids, and cacti. Evergreens were represented by laurels, cypresses, and yews, while deciduous trees belonged to such forms as maple, plane,

[1] Characteristic fossils of the chief sub-divisions of the English Eocene are represented by the illustrations, figs. 318 to 357.

willow, poplar, elm, beech, chestnut, buckthorn, hornbeam, walnut, fig, etc. Altogether the flora of the Eocene had an Indo-Australian character.

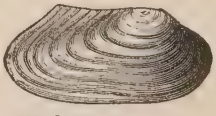
The protozoans of the Eocene period are represented most characteristically by foraminifera—some forms of which (*Miliola*, *Nummulina*) give rise to thick limestones. Corals, mostly of modern

325. Melania inquinata.

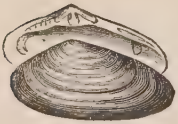
326. Pitharella Rickmanni.

327. Cerithium funatum.

328. Cyrena cordata.

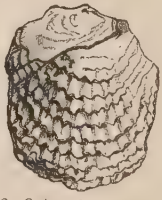


329. Unio subparallela.



330. Cyrena telinella.

331. Ostrea tenera.



332. Ostrea Bellovacina.

Figs. 325 to 332.—FOSSILS FROM THE WOOLWICH AND READING BEDS.

types, are not very abundant. Sea-urchins are fairly numerous, but crinoids, formerly so common, are now very meagrely represented. Brachiopods also are now greatly reduced in numbers—the principal genera being the existing forms *Terebratula* and *Rhynchonella*. Lamellibranchs and gasteropods, especially the siphonostomatous forms, on the other hand, abound exceedingly—the genera being chiefly modern, and suggestive of warm seas; among these are *Conus*, *Voluta*, *Cypræa*, *Oliva*, etc. One of the most common of

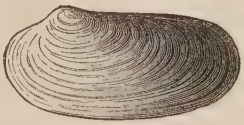
the gasteropods is *Cerithium*. The Ammonitidæ are now extinct

333. Pleurotoma prisca.

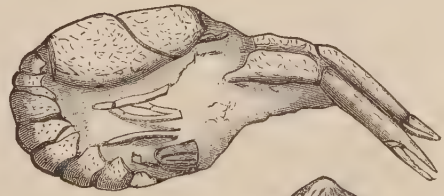
334. Nautilus imperialis.

335. Voluta Wetherelli.

336. Hoploparia gammaroides.

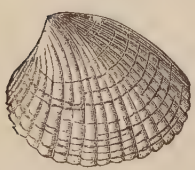


337. Panopæa intermedia.



339. Hoploparia Bælli.

338. Terebratulina striatula.



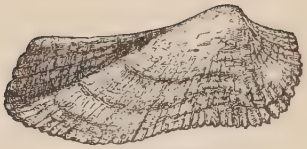
340. Cardita Brogniarti.

341. Cassidaria striata.

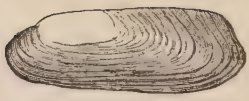
342. Nipa elliptica.

Figs. 333 to 342.—FOSSILS FROM THE LONDON CLAY.

—the tetrabranchiate cephalopods being represented principally



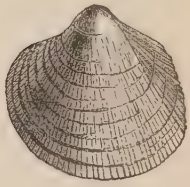
343. Arca biangula.



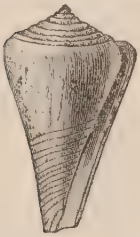
344. Sanguinolaria Hollowaysii.

345. Chama squamosa.

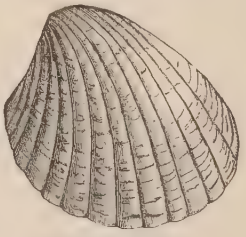
346. Cardium porulosum.



347. Cardium semigranulatum.



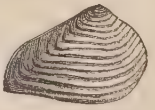
348. Conus deperditus.



349. Cardita planicosta.

350. Oliva Branderi.

351. Murex asper.



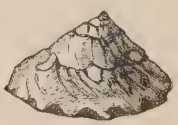
352. Crassatella sulcata.

354. Turritella imbricataria.

355. Fusus longævus.

356. Voluta athleta.

353. Ancillaria fusiformis.



357. Phorus agglutinans.

Figs. 343 to 357.—FOSSILS FROM THE BRACKLESHAM AND BARTON BEDS.

by the still existing genus *Nautilus*. The Belemnitidæ are also unrepresented. The fishes of the Eocene are represented by teleosteans, a few ganoids and placoids. The latter are known chiefly through their teeth, common forms being *Otodus*, *Lamna*, *Carcharodon*, etc. The reptiles consist of turtles, terrapins, snakes, lizards, crocodiles, and alligators ; none of the great Mesozoic saurians survived into Eocene times. The birds are well represented. Among Lower Eocene forms were *Odontopteryx*, the jaws of which had tooth-like denticulations ; *Argillornis*, apparently akin to the albatross, *Halcyornis*, probably a king-fisher, besides forms of heron, gull, vulture, and a large bird (*Dasornis*) allied apparently to the extinct *Dinornis* of New Zealand. In the Upper Eocene of the Paris basin remains of ten species occur, some of them allied to the buzzard, woodcock, quail, pelican, ibis, flamingo, and African hornbill. The most noteworthy forms of the Eocene period, however, are the mammals. From the Lower Eocene come various animals which have certain characters intermediate between marsupials and carnivores. Thus *Arctocyon* had a marsupial-like brain and bear-like teeth ; *Palæonictis* had likewise marsupial affinities, and was provided with teeth like those of the Tasmanian dasyure. Other Lower Eocene forms were *Coryphodon*, a large tapiroid animal ; the small hog-like or hyrax-like *Hyracotherium*, with teeth resembling those of the peccary ; and the allied genus *Pliolophus*. In Middle Eocene times various tapiroid forms made their appearance, such as *Lophiodon*, *Palæotherium*, *Paloplotherium*, etc., associated with which were true carnivores and animals allied to carnivores and hogs. At this stage also appears the earliest of the Prosimiæ — the lemuroid *Cœnopithecus* of the Swiss Eocene. One of the most noteworthy animals of the Upper Eocene is the *Anchitherium*, which had affinities to the tapir-like palæotheres and true horses. Each foot had three hoofs that reached to the ground. This animal was about the size of a small pony, and is believed to be an ancestor of the horse. Tapir-like animals abounded, such as *Palæotherium*, and there were also many hog-like animals with intermediate or generalised characters, as well as transitional hornless forms of deer and antelopes. Carnivores seem to have been numerous, all of them having marsupial affinities.

From the American Eocene have been obtained remains of some remarkable types. Among these are four-toed (*Orohippus*) and five-toed (*Eohippus*) ancestors of the horse, and *Dinoceras*, an animal as large as the elephant, provided with a pair of horn-like processes on the snout, two large ones on the maxillaries, and another pair on the forehead. The upper jaw was furnished with two long tusk-like canines.

Physical Conditions.—The Eocene deposits of the Anglo-French and Belgian area appear to have accumulated in an inland sea opposite the mouths of one or more great rivers. That sea, however, probably had some communication with the Atlantic in the direction of what is now the English Channel. Although the strata as a whole are marine, yet the occurrence in the Woolwich and Reading series of fresh-water beds charged with fluviatile shells, and the frequent appearance of land-plants and remains of terrestrial animals in nearly all stages of the system, suffice to show that the Eocene strata were accumulated chiefly under estuarine conditions, which were most marked at the beginning of the period. The oldest Eocene beds rest unconformably upon the Cretaceous strata—so that a break in the succession occurs. A movement of elevation followed upon the close of the Cretaceous period, and the sea disappeared from Middle Europe. Probably the British area at this time was connected with what are now the opposite coasts of the Low Countries and Northern France, and considerable denudation of the later Cretaceous deposits supervened. Erelong, however, partial subsidence set in, and at the beginning of the Eocene period the sea commenced to invade the Anglo-French and Belgian areas—the depression reaching its maximum apparently during the deposition of the London Clay. The rivers entering that inland sea flowed through continental lands covered with a tropical vegetation, consisting of palms, cypresses, banksias, etc. Probably one great river came from the north, draining the uplands of Eastern Britain and Southern Norway. Its waters were haunted by turtles, by alligators, crocodiles, and gavials, while the neighbouring sea swarmed with sharks, sword-fishes, and ganoids ; and, as marking the genial temperature, we may note amongst the molluscan forms nautilus, cones, volutes, cowries, and olives—types which are now only met with in warm southern seas. Various species of nummulites were more or less abundant, especially in the French area, but it was in the seas of Southern Europe that they attained their greatest development. In Eocene times the Mediterranean could hardly have been described as an inland sea, but, extending north and south over broad areas which are now dry land, it stretched east into Asia, and apparently communicated with the Indian and Pacific Oceans. At that time some of the most prominent mountains of the old world were inconspicuous elevations—the Pyrenees, the Alps, the Carpathians, and even the Himalaya were then pigmies as compared to their present selves. Since the Nummulitic sea washed their slopes they have been upheaved for thousands of feet —the Eocene calcareous strata which enter into their formation being often as hard and crystalline as any of the older rocks against

which they abut. To-day these limestones occur in the Pyrenees and the Alps at heights of over 10,000 feet, while in the Himalaya the old sea-floor of Eocene times has been upheaved to an elevation of 16,500 feet.

The climate of the Eocene, as we have seen, had quite a tropical character. But whether such conditions obtained throughout the period we cannot be certain. Mr. Starkie Gardner has pointed out that the plants of the Woolwich and Reading series have, upon the whole, a temperate aspect. It was not until later on in the period (London Clay, etc.) that the Eocene flora of our area assumed its Indo-Australian character. Moreover, the occurrence in the Flysch of the Alpine lands of numerous erratics, some of which exceed 100 feet in diameter, speak to us of considerable icebergs. If these erratics came from the Archæan rocks of Bohemia, it is evident that they betoken the former existence of large glaciers which descended to the sea-level and there set their bergs adrift. The nearest analogy to this that we have at present is in New Zealand, where, between lat. 43° and 44° S., glaciers descend to within 500 feet of the sea-level, and deposit their moraines in a region of tree-ferns and Areca palms.

II.—OLIGOCENE.

The British strata pertaining to this group occur only in Hampshire, the Isle of Wight, and Devonshire. In the two former localities there is no break between the Eocene and Oligocene, but a gradual conformable passage. Formerly the lower portions of the series here termed Oligocene were included in the Eocene, while the highest group was termed Miocene. But the insertion of the term Oligocene has been rendered necessary in order to bring our classification into harmony with that adopted by geologists on the Continent, where the equivalents of the British series are well developed.

The British Oligocene beds are classified as follows :—

4. Hamstead beds.
3. Bembridge beds.
2. Osborne or St. Helen's beds.
1. Headon beds.

The *Headon beds* consist of a variable series of clays, marls, sands, and limestones. The lower portion of the group is of fresh- and brackish-water origin ; the middle is partly marine, partly estuarine ; and the upper fresh-water.

The *Osborne beds*, consisting of marls, clays, sands, calcareous grit, and limestone, are fresh-water.

The *Bembridge beds* are a series of fresh-water limestone, sands, marls, and clays.

The *Hamstead beds* consist of a series of fresh-water marls and clays, capped by septarian clays of marine origin.

These groups, which are confined to the Isle of Wight and the adjacent Hampshire area, attain a thickness in all of about 400 feet. They are often spoken of as the "fluvio-marine series."

Usually included as Oligocene are the plant-beds of Bovey Tracey and the leaf-beds of Antrim, Mull, etc. Mr. Starkie Gardner, however, ranks them as Eocene.

The *Bovey Tracey beds* occur in a small detached area in Devonshire, where they evidently occupy a lacustrine hollow. They are from 200 to 300 feet in thickness, and consist of a series of sands, clays, and lignites. The *Leaf-beds of Antrim, Mull, and Skye*, occur as local lenticular layers of clay and lignite, intercalated here and there between sheets of basalt.

Foreign Oligocene.—Oligocene deposits, partly of marine and partly of fresh-water and estuarine origin, are met with overlying the Eocene of the Paris basin and the Belgian area. They likewise appear in North Germany, where they form the oldest Tertiary deposits—no Eocene strata having yet been recognised in that region. The North German Oligocene strata are developed chiefly in three regions, namely, in the Rhine valley, where they extend from south of Bonn up to the borders of Belgium and Holland; in Saxony, whence they stretch from Halle into the region of the older rocks of the Thüringerwald; and in Lower Silesia. They consist of marine deposits and fresh-water accumulations. With these are associated numerous seams of brown coals, which occur in irregular lenticular layers of very variable thickness, beds of from 3 feet to 10 feet thick being common, while in some cases an individual seam may reach 150 feet. The strata with which these coals are associated consist chiefly of gravel and conglomerate, sands and sandstone, and grey and white plastic clay. The coals are composed principally of the remains of conifers and cypresses, together with marsh- and water-plants. In the clays and sandstones occur the leaves of many trees, such as species of oak, laurel, cinnamon, magnolia, dryandroides, fig, sassafras, alder, maple, walnut, birch, and palms. The marine strata consist for the most part of sands, sandstone, and clay, more or less abundantly charged with marine organisms, foraminifera and molluscs (chiefly lamellibranchs and gasteropods) being especially conspicuous. The German Oligocene is mainly of fresh-water origin in its lower and

upper portions, while marine deposits predominate in the middle of the series.

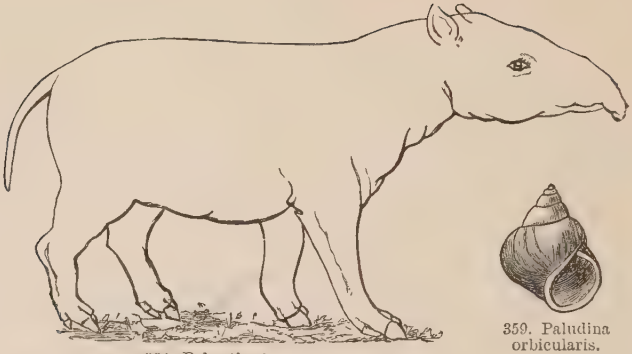
In Switzerland a great thickness of conglomerates and sandstones known as *Molasse* overlie the Nummulitic and Flysch formations. The lower portions of this Molasse pertain to the Oligocene, the upper portions being of younger Tertiary age. The Oligocene Molasse consists of a lower series of sandstones (Lower Marine Molasse) containing marine and brackish-water shells, and an upper series of parti-coloured and red marls, 1000 feet thick, overlaid by sandstones, marls, and conglomerates (Nagelfluh), containing lenticular beds of brown coal, many fresh-water shells, and abundant plant-remains, comprising species of cinnamon, dryandroides, evergreen oaks, fig, alder, birch, walnut, sequoia, pine, and palms—the flora having a general subtropical-American facies like that of Louisiana and Florida, modified by the presence of certain Japanese and Australian forms.

Other localities for European Oligocene are Alsace, where a series of brackish and marine strata occur; Breisgau, Würtemberg, and other places in South-west Germany, and the neighbouring parts of Switzerland and France, where certain mineral-spring accumulations (Bohnerz formation) have yielded remains of Tertiary mammals; Auvergne, where massive fresh-water deposits occur, richly charged with the remains of mammals, reptiles, and birds; and the Vienna basin, where a considerable series of fresh-water and marine strata have been met with, from which numerous mammalian and other remains have been obtained.

Life of the Period.[1]—The flora of the Oligocene was abundant and varied. Palm trees seem to have grown over all Europe. There were large and small kinds, the former (*Sabal*, *Flabellaria*) exceeding in size their nearest living allies. Amongst the conifers were various American types (*Libocedrus*, *Chamæcyparis*, *Sequoia*, *Taxodium*) and other forms, such as *Glyptostrobus*, like *G. heterophyllus* of Japan and China, *Widdringtonia*, a genus now found only at Cape of Good Hope and Madagascar. There were also proteaceous plants (*Dryandra*) of Australian affinities; and species of custard-apple, gum-tree, spindle-tree, maple, acacia, mimosa, lotus, aralia, camphor-tree, cinnamon-tree, evergreen oak, laurel, etc., besides such familiar forms as birch, hornbeam, alder, elm, poplar, walnut, etc. Evergreens were the prevalent forms.

The invertebrate fauna needs but little notice here. Siphonostomatous gasteropods, such as volutes, cowries, olives, cones, spindle-shells, etc., are common. *Cerithium* often abounds in brackish-

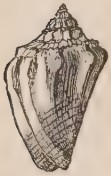
[1] Characteristic fossils of the English Oligocene are shown in figs. 358 to 369.



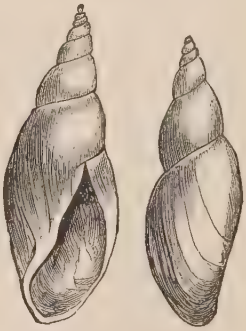
358. Palæotherium magnum.

359. Paludina orbicularis.

360. Chara medicagulina.



361. Voluta Rathieri.



362. Limnæa longiscata.

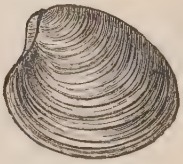
363. Bulimus ellipticus.

364. Helix occlusa.

365. Helix globosa.

366. Planorbis euomphalus.

367. Cerithium Sedgwicki.



368. Cytherea incrassata.

369. Natica depressa.

Figs. 358 to 369.—FOSSILS FROM THE HEADON AND BEMBRIDGE BEDS.

water strata, and lamellibranchs are well represented by marine and fresh-water forms, all of modern types. Amongst the birds of the period were parroquets, trogons, marabouts, cranes, flamingoes, ibises, pelicans, eagles, secretary-birds, sand-grouse, etc. At the beginning of Oligocene times many mammals of extinct types lived in Europe, such as *Palæotherium* and *Anchitherium*, survivals from the Eocene, small deer-like animals (*Cainotherium, Xiphodon, Anoplotherium*), tapirs, small rhinoceroses, opossums, *Hycænodon*, a carnivore combining characters of a placental mammal with those of a marsupial, also species of squirrel, civet, martin, mole, musk-rat, etc.

Physical Conditions.—The Oligocene strata of the south of England and the Franco-Belgian area are evidence that the Eocene sea or estuarine waters were gradually silted up, a process which must have occupied a long time—a time during which considerable changes in the fauna and flora came about. The climate continued genial, but was hardly so tropical as that of the preceding period. The lower reaches of the rivers were still frequented by many turtles, crocodiles, and alligators, while rays, sharks, and cetaceans (*Balænoptera*) abounded in the adjacent sea. Numerous extinct forms of pachyderms and deer-like animals roamed over the land, which supported a sub-tropical flora, comprising such plants as palms, large conifers, cinnamon-trees, gum-trees, evergreen oaks, figs, laurels, vines, and others. A wide land-surface appears to have extended over all the British area. In the far north, in the region lying between what is now Antrim and the west coast of Scotland, enormous fissure-eruptions took place, and sheet after sheet of basalt was poured out, so as eventually to form great plateaux that extended northwards beyond the island of Skye. In the intervals between successive eruptions these plateaux became covered with vegetation, the débris of which has been here and there preserved in the deposits of shallow lakes that dotted the surface of the volcanic country. It is probable that at this time there was land-connection between Europe and North America by way of the Faeröe Islands and Iceland, in both of which tracts similar basaltic plateaux occur, containing intercalated layers of lignite, etc., of the same character as those of Antrim and the Western Islands of Scotland. Some idea of the extent of those outpourings of lava may be gathered from the fact that after enormous denudation the beds are still 900 feet thick in Antrim, 3000 feet in Mull, and 13,000 to 14,000 feet in the Faeröe Islands.

In North Germany there existed great fresh-water lakes, fringed by wide stretches of marsh and by thick forests of a sub-tropical character. As the lakes became partially silted or dried up vege-

tation encroached upon their deserted beds, only to be buried under new accumulations of sand and mud when the waters had again risen. That these lakes were now and again in direct communication with the sea is shown by the occurrence of thick layers of marine origin intercalated amongst the fresh-water beds. For some time the lacustrine areas were usurped by the sea, which may have entered them from submerged regions in the east of Europe.

In Switzerland, in like manner, we have evidence of changing conditions. At first the sea covered a considerable portion of the country, but eventually it disappeared, and its place was taken by a series of brackish-water lagoons and fresh-water lakes.

In Central France, as in Germany, lacustrine conditions were characteristic of the period, one or more great lakes having covered a considerable area in Auvergne.

In Southern Europe the Mediterranean had withdrawn from wide regions which were deeply submerged by it in Eocene times, but it still covered a more extensive area than at present.

III.—MIOCENE.

No true Miocene deposits occur in Britain—the beds formerly classed as Miocene having now been included in the Oligocene. On the Continent they are well represented, but do not spread over such wide areas as the earlier Tertiaries. In the west of France marine Miocene deposits of shallow-water origin cover considerable regions in the low grounds of Touraine (*Faluns de la Touraine*), containing an abundant marine fauna, together with remains of various terrestrial animals which had doubtless been washed down by rivers to the sea. Marine deposits of Miocene age (*Black Crag*) are likewise sparingly developed in Belgium. Nowhere in the eastern regions of North Germany has any trace of beds of Miocene age been discovered; they occur, however, in the so-called Mayence basin, which extends from the Taunus on both sides of the Rhine as far south perhaps as Basel. The beds consist of a very variable series of sandstones and limestones chiefly of fresh-water origin—the sandstones containing leaves of species of cinnamon-tree, oak, elm, evergreen oak, magnolia, acacia, gum-tree, fig, vine, palms, and cypresses, while the limestones are made up of the shells of fresh-water molluscs (*Corbicula*, *Littorinella*). The lower beds are marine. Mammalian remains occur, as *Cainotherium*, *Hippotherium*, species of *Rhinoceros*, deer, etc.

A much more important series of Miocene deposits is developed in the Vienna basin—a broad tract, bounded on the east by the Carpathians, on the south by the Eastern Alps, and on the west by

the plateau of Moravia and Bohemia. The deposits consist of a very variable succession of sands, sandstones, clays, marls, and limestones—the lower portion of the series being marine (Mediterranean stage), while the upper portion (Sarmatian stage) is less distinctly so, many of the shells indicating brackish conditions. The lower or Mediterranean stage contains both deep-water and littoral deposits, and the abundant forms of shells and corals have quite a tropical or sub-tropical aspect, and indicate a sea which had free communication with the open ocean. In the Sarmatian stage the molluscan forms are much less numerous, although individual species abound. The tropical and sub-tropical forms are no longer present, the general facies of the shells being temperate. In the Mediterranean stage occur locally some fresh-water beds from which have been obtained relics of an abundant flora, comprising palms (*Sabal, Phœnicites*); conifers (*Libocedrus, Sequoia*); species of oak, fig, laurel, cinnamon, various proteaceous plants (*Banksia, Dryandra*); olive, ebony, magnolia, maple, soap-tree, holly, walnut, varnish-tree, myrtle, mimosa, acacia, etc. Contemporaneous with this flora were *Mastodon*, *Dinotherium*, *Anchitherium*, *Hyotherium*, species of *Rhinoceros*, and tapir, fox (*Amphicyon*), and others. Some of these mammals occur also in the Sarmatian stage, but the flora of this upper group differed considerably from that of the lower stage. Among the characteristic forms of the younger Miocene were conifers (*Glyptostrobus, Sequoia, Pinus*); and species of birch, alder, oak, beech, chestnut, liquid-ambar, plane, willow, poplar, laurel, cinnamon, etc. While the sea of the Vienna basin was in full connection with the open ocean the climate would thus appear to have been tropical or sub-tropical—the general character of the flora being Indo-Australian. Afterwards, when the Vienna sea lost immediate connection with the ocean, its waters became less saline, like those of the Black Sea. The climate at the same time lost its tropical character, although it still remained warm, as we may infer from the general aspect of the flora—the nearest living representatives of the more characteristic plants occurring in Asia Minor, the Caucasus, the Himalaya, Central and Northern Asia, and Japan.

Miocene beds are disclosed at various points in Schleswig-Holstein, Mecklenburg, Hanover, Oldenburg, Westphalia, etc.; but over North Germany they are for the most part concealed underneath the alluvial and glacial accumulations of later times. They are, however, well developed and exposed in Switzerland and south Bavaria. The succession of beds in those regions is as follows:—

1. *Upper Fresh-water Molasse*, or Œningen stage: sandstones, marls, and limestones, with occasional brown coals. Plants abundant:

American and European types abound ; Asiatic, African, and Australian forms very much reduced.

2. *Upper Marine Molasse*, or Helvetian stage : variable series of sandstones which are occasionally conglomeratic. Of the molluscs, 35 per cent are living species, some occurring in the Mediterranean and others in tropical seas. Many of the shells are of the same species as occur in the Miocene of the Vienna basin.

3. *Lower Fresh-water or Grey Molasse*, or Mayence stage : chiefly sandstones with plentiful plant-remains, which have a decidedly North American character. A marine bed is intercalated in the group.

In North America Miocene strata occur sparingly on the Atlantic borders of the Eastern States, where they are of marine origin. In the Rocky Mountain region they are represented by thick and widespread lacustrine formations, from which a large series of mammalian remains have been obtained. Far north, within the Arctic Circle, more or less abundant traces of strata occur which contain the relics of a flora having the same character as that of the Miocene of Central Europe. The evidence of the plant-beds of Greenland, Iceland, Bear Island, and Spitzbergen proves that during Tertiary times a luxuriant flora extended to within a few degrees (8° 15′) of the pole. Many of the plants (such as species of *Taxodium*, *Sequoia*, *Glyptostrobus*, *Sclerotherium*, *Corylus*) are identical with European Miocene forms. According to Heer, the Miocene flora of Greenland contained 13 large ferns, 17 conifers, 17 monocotyledons, and 112 dicotyledons, including such trees as walnut, plane, beech, oak, maple, and poplar, besides ivy and the vine. All these plants grew *in situ*. In some places thick beds of coal occur, as at Watercourse Bay, on the west side of Smith Sound, in lat. 81° 45′ N., where the coal is 25 to 30 feet thick. Associated with this coal were such plants as birches, poplars, pines, firs, spruce, elm, and hazel.

Life of the Period.—A list of some of the plants obtained from the Miocene of the Vienna basin has already been given, and might be extended by taking the Swiss Miocene plants into account. But, from those mentioned, we may gather that the climate of Central Europe in early Miocene times was tropical, the nearest representatives of many of the more characteristic plants being confined now to India and Australia. The flora of the later stages indicates a more temperate climate. The molluscan forms are all modern types, but those pertaining to the older Miocene have a tropical or sub-tropical facies, while the shells in the younger strata seem, like the plants, to betoken milder conditions. Amongst mammalian forms the more notable were the proboscideans, *Dino-*

therium and *Mastodon;* species of *Rhinoceros*, one with and another without horns; *Anchitherium*, a small tapiroid horse-like animal, surviving from Eocene times; *Macrotherium*, a kind of gigantic ant-eater; *Helladotherium*, allied to the giraffe; various antelopes and deer with small horns and antlers; and *Machairodus*, a lion-like sabre-toothed carnivore. Apes (*Pliopithecus, Dryopithecus*, etc.), were also among the denizens of Miocene Europe.

Physical Conditions.—In Miocene times the British area, so far as we know, was dry land, and the same was probably the case with all Northern Europe. The sea, however, would seem to have overspread the low grounds of Belgium, and to have extended over a considerable area of North-west Germany. Perhaps at this time Schleswig-Holstein, Hanover, and the Low Countries were under water. In like manner some of the low-lying maritime regions in the west of France were submerged, and the same was the case with considerable tracts in the south and east of Spain. From the Gulf of Lyons a long branch of the sea passed up the valley of the Rhone, and swept north-east through Northern Switzerland, sending an arm into the Mayence basin, and then traversing Bavaria, across which it probably continued until it communicated with the wide sea which then occupied all the great plains of Hungary. Northern and Eastern Italy were at the same time under water, as was also the case with many other regions in Eastern Europe and Asia Minor. Indeed, the distribution of the Miocene leads to the belief that Southern Europe at that time was an extensive archipelago, in which such regions as the plateaux of Spain and Central France, the Pyrenees, the Alps (along with a part of the contiguous countries ranging south-east by Dalmatia into Greece), the Carpathians, etc., existed as islands. In the north of Europe, then, lay the chief land-mass—a land clothed with a most luxuriant vegetation, and doubtless tenanted by a copious fauna. If the Miocene strata of the Arctic regions be of the same age as the Miocene of Central Europe, then we may infer that a vast area of the North Atlantic existed as dry land, across which migrations of the flora took place. Some geologists, however, consider that the Miocene of Greenland, etc., probably dates back to earlier Tertiary times. They think that the sequoias, oaks, walnuts, hazels, etc., of those high latitudes were contemporaneous with the tropical flora of Eocene Europe; and that after Eocene times, when the climate of our continent had become less tropical, the then Arctic flora gradually spread southwards until it predominated in Europe. Before the close of Miocene times considerable elevation of the land seems to have taken place, and the sea disappeared from wide regions which it had formerly occupied in North-west Germany and Central

Europe. The Mayence basin became a fresh-water lake, and one or more similar lakes replaced the Miocene sea of Switzerland. At the same time the wide sea which overflowed the Vienna basin and the plains of Hungary was much reduced in extent, and, being shut off from immediate connection with the open waters of the Mediterranean area, it became somewhat freshened—the conditions resembling those that characterise the present Black Sea.

The climate of Lower Miocene times was, as we have seen, decidedly tropical—the deposition of the Upper Miocene having taken place under less extreme conditions. It is remarkable that the Upper Miocene of Northern Italy contains a thick series of unfossiliferous sandstones and conglomerates in which occur many large angular erratics, some of them smoothed and glaciated on one or more sides. One of these blocks measured 26 feet across. They consist of various crystalline rocks and limestones which may have come from the Alps ; and, according to Signor Gastaldi, they must have been transported by floating ice. Erratics have also been noted in Miocene strata in France and Spain.

IV.—PLIOCENE.

Pliocene deposits are very poorly developed in the British area, and are restricted to a limited region in the counties of Essex, Suffolk, and Norfolk. They consist of irregular lenticular beds of sands and shelly gravels, etc., which never all occur together in one place. The whole series probably does not exceed 120 feet in thickness, and the individual groups thicken and thin out irregularly. They are arranged as follows :—

6. Cromer Forest-Bed Group.
5. Chillesford and Weybourn Crags.
4. Norwich Crag.
3. Red Crag.
2. St. Erth Beds.
1. Coralline Crag and Lenham Beds.

The *Coralline Crag* consists chiefly of light yellowish, soft, marly sands, with here and there thin flaggy limestones. In places it is composed almost entirely of Polyzoa (popularly called *corals*, hence the name of the group). It contains 317 species of shells, of which 84 per cent are still living. Of the marine forms 14 are now restricted to Northern seas and 65 to Southern Seas. The water in which the Coralline Crag accumulated appears to have been of moderate depth —50 to 70 fathoms.

The *Red Crag* is chiefly red ferruginous sand, crowded in many

places with shells entire and broken. It rests here and there in hollows of the Coralline Crag, but as a rule the deposits lie side by side. About 90 per cent of the shells of this group are existing species—23 species now confined to Northern Seas and 32 to Southern Seas. Besides these shells bones and teeth of many land-animals occur, several referable to Miocene forms, such as *Hipparion*, *Halitherium*, *Hyænarctos*, etc. Many of the fossils referred to are rolled and water-worn, and have probably been derived from some pre-existing Miocene beds. The Red Crag is a shallow-water deposit.

The *Norwich Crag* is a fluvio-marine accumulation of gravel, sand, and loam, only a few feet in thickness, which appears to have been deposited in the sea opposite the mouth of a river. It has yielded 163 species of mollusca, of which 93 per cent are still living; 19 being now restricted to Northern Seas and 11 to Southern Seas. Several species of fresh-water shells occur, most of them being existing forms. Mammalian-remains, especially those of elephants, have frequently been obtained from this deposit, hence the name "Mammaliferous Crag" sometimes applied to it.

The *Chillesford Beds* consist of sand and clay; and contain a number of shells, two-thirds of which are still living in Arctic Seas.

The *Forest-Bed Group* is a thin series of fresh-water and estuarine silts or clays overlaid by marine sands, etc. The fresh-water beds contain layers of peat, a "rootlet bed" marking an old land surface, and much vegetable matter. The plants consist of Scots fir, spruce fir, yew, alder, oak, hazel, white and yellow water-lilies, bogbean, common sloe, etc. Along with these occur the remains of many mammals, including extinct species of elephant, rhinoceros, machairodus, bear, many deer, and other animals, some of which are still living, such as glutton, wild boar, hyæna, etc.

Foreign Pliocene.—Highly fossiliferous marine sands of Pliocene age occur in the neighbourhood of Antwerp, which are believed to be the equivalents of the English Coralline and Red Crags. No marine Pliocene occurs in the north of France; but beds of this age are met with in the west, as in Cotentin, Morbihan, and Aquitaine. Again in the south beds of sandy marls and conglomerates occur in the maritime districts of Rousillon and Languedoc. Along with marine shells some of these beds have yielded mammalian remains, such as *Mastodon*, *Rhinoceros*, *Tapirus*, and *Elephas meridionalis*. Marine Pliocene is fairly well developed also in the lower reaches of the Rhone valley, reaching as far north as Lyons. The upper beds in some places contain many plant remains. The limits reached by the Pliocene sea are marked out in places by coarse quartzose conglomerates. In various parts of France fresh-

water deposits of the same age have yielded abundant relics of the Pliocene flora and fauna. Among those the more notable are the calcareous tufa of Meximieux, remarkable for its plants; the marls and sands of the basin of the Saône, from which numerous mammalian remains have been obtained; the ossiferous gravels of Perrier; and the plant-bearing volcanic tuffs of Cantal, which occur at heights of nearly 3000 feet.

Among the most important Pliocene deposits in Middle Europe are the fluviatile sand and gravel, which overlie the Miocene of the Mayence basin. These beds contain lignites composed of plants of North American types, and have yielded various mammalian remains such as *Dinotherium*, *Hippotherium*, *Anthracotherium*, *Mastodon*, *Rhinoceros*, etc. Another important area of Pliocene is that of the Vienna basin. The series consists of two groups:—

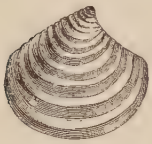
2. *Belvedere Stage:* beds of fluviatile gravel and sand.
1. *Congeria Stage:* partly clay, and partly gravel and sand; brackish-water molluscan fauna; contains many mammalian remains and plants.

In Italy marine Pliocene beds appear at various points at the foot of the Alps, and along both flanks of the Apennines, where they form what has been termed the sub-Apennine formation. They attain a thickness of about 3000 feet, and have yielded a large series of fossils—many of the molluscs being tropical forms. Here and there plant-remains occur of types which recall the flora of Madeira and the coast-lands of the Mexican Gulf. To the Pliocene also belongs a thick series (2000 feet) of marine deposits, which occur in Sicily up to heights of over 3000 feet. The beds are abundantly charged with shells and corals, the larger number of which in the upper beds belong to living Mediterranean species. The older tuffs and lavas of Etna are inter-stratified with these marine accumulations.

Life of the Period.[1]—The rich and abundant vegetation of the Miocene, in which evergreens preponderated, was represented in Pliocene times by many identical or nearly allied species; but the palms and other characteristic forms had disappeared. The Pliocene flora was richer in genera than that of the present day, and some of these genera were richer also in species. It was a singularly uniform flora; for the assemblage of plants in the Pliocene of Bologna and Tuscany is much the same as that which occurs near Lyons and in the Cantal. Ivy, platanus, liquidambar, various maples, many walnut trees, elms, hornbeams, magnolia, tulip tree,

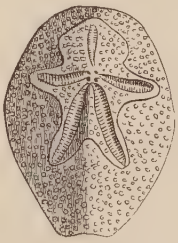
[1] Characteristic fossils of the English Coralline and Red Crag deposits are shown in figs. 370 to 385.

Canary laurel, oleander, vine, glyptostrobus, sassafras, and others, ranged from Central Italy to the heart of France—such plants as beech, poplar, elm, lime, oak, various conifers, sassafras, maples, bamboos, vines, etc., growing up to the crests of the mountains in Cantal. It was evidently an abundant vegetation, composed for the most part of large trees, some of which were survivors from the Miocene, destined soon to become extinct; some again were

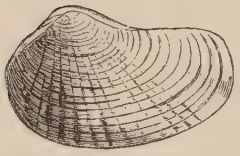


370. Astarte Omallii.

371. Cyprina rustica.



373. Brissus Scillæ.



372. Pholadomya Hesterna.

374. Pecten opercularis.

375. Fascicularia aurantium.

376. Glycimeris angusta.

377. Terebratula grandis.

Figs. 370 to 377.—FOSSILS FROM THE CORALLINE CRAG.

special forms belonging to genera which are now exotic; others were species which have survived to the present in more southern and eastern regions, while yet others are still represented in Europe by identical or closely-allied species. Thus, according to Saporta, the Pliocene flora is connected both with the past and the present plant life of Europe, while at the same time it has relations with the floras of distant southern and eastern regions—regions now separated by wide stretches of sea—North America, the Canary

Islands, Eastern Asia, Japan, and China. The abundant evergreen plants seem to have flourished chiefly on the low grounds; at higher elevations pines and deciduous trees were the prevailing forms. Farther north doubtless the flora would be similarly modified by latitude. The flora of the Norwich Crag shows that towards the close of the Pliocene period the British area was clothed with a vegetation not greatly differing from that of the present.

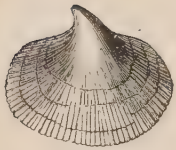
The molluscan fauna includes an increasing number of living

378. Trophon antiquus.

379. Cassidaria bicatenata.

380. Buccinum Dalei.

381. Voluta Lamberti.



382. Capulus ungaricus.

383. Cardium Parkinsoni.

384. Pectunculus glycimeris.

385. Carcharodon megalodon.

Figs. 378 to 385.—FOSSILS FROM THE RED CRAG.

species. In the lower Pliocene the general facies is still southern; but in the upper groups southern types gradually diminish in importance, and are replaced by temperate and northern forms. Amongst mammals we find several survivors from the Miocene, such as *Dinotherium*, *Mastodon*, *Hippotherium*, and *Helladotherium*; and one at least from still older Tertiary times, namely the *Anthracotherium*. Along with these were various species of elephant (particularly *E. meridionalis*), rhinoceros, hippopotamus, tapir, a

three-toed horse (*Hipparion*) as well as the existing *Equus;* also many forms of cervine and bovine animals; several carnivores allied to lynx and panther, bears, wolves, hyænas, *Machairodus*, and several apes. The Pliocene beds of the Punjaub and the sub-Himalaya (Siwalik beds) have yielded a large number of mammalian remains consisting of extinct and living types, amongst the former being *Hyænarctos*, *Machairodus*, and others which date from the Miocene; and *Sivatherium*, a gigantic two-horned antelope. With these are associated many modern genera such as *Felis*, *Hyæna*, *Canis*, *Bos*, *Bison*, *Capra*, *Ovis*, etc. It may be noted also that from the Pliocene of the Upper Missouri region of North America have been obtained remains of an abundant mammalian fauna, comprising species of camel (the oldest known), rhinoceros, mastodon, elephant; several cervine and equine animals, one very like the modern horse but larger; wolf, fox, tiger, beaver, porcupine, etc.—a fauna which has a strikingly Oriental character.

Physical Conditions.—The movement of elevation which accompanied the deposition of the Upper Miocene of Central Europe was continued into Pliocene times, so that eventually the sea retreated from Switzerland and the Mayence basin. It still, however, overflowed a vast area in South-eastern Europe, extending through the Aralo-Caspian depression into Asia. The wide sea which had covered such vast areas in Austro-Hungary was now much reduced in extent; that portion which occupied the Vienna basin becoming gradually freshened by the influx of great rivers which eventually silted it up, while other isolated portions of the same Upper Miocene sea formed salt-lakes, over the beds of which, as the waters evaporated, abundant depositions of rock-salt and gypsum took place. The Mediterranean, considerably reduced in extent, nevertheless still covered many tracts which are dry land to-day. The valley of the Po then formed a great arm of the sea which penetrated the mountain-valleys of the Alps, while Italy and Sicily were largely submerged. The lower reaches of the Rhone valley and considerable tracts in the maritime districts of Western France were likewise under water; and the North Sea encroached upon the low grounds of Belgium and East Anglia.

One of the most notable events of the Pliocene was the birth of Etna and Vesuvius. The earliest eruptions appear to have taken place in the bed of the sea which was gradually elevated towards the close of the period, so that before the advent of the succeeding Pleistocene period the sea had retired from the great valley of the Po, and Italy and Sicily had acquired nearly their present extent, while Etna had risen into a great sub-aërial volcanic mountain.

The fauna of early Pliocene times unquestionably indicates warm

climatic conditions, and the associated flora tells a like tale. During the earlier stages of the period the shores of North-western Europe were washed by genial waters, in which lived many molluscs, which must now be sought for in the seas of more southern latitudes; while in the Mediterranean tropical forms, such as cones, cowries, wing-shells, fig-shells, mitre-shells, olives, auger-shells, seraphs, etc., abounded. As we advance to later stages of the period, however, we meet with evidence of a gradually deteriorating climate. In the English Pliocene strata occasional erratics occur which speak to us of floating ice, while the southern forms of molluscs become less numerous at the same time that immigrants from the north increase in numbers. Similar proofs of changing conditions are met with in the marine Pliocene of the Mediterranean area. It is the same with the flora. The plants of the fluvio-marine beds (Norwich Crag) indicate a climate perhaps a little colder, but not essentially differing from that of Norfolk at present. But as the plants were traced upwards through the strata they were found by Dr. Nathorst to become more and more stunted and meagre, until in a bed immediately underlying the Cromer boulder-clay he came upon the Arctic willow (*Salix polaris*) and a moss (*Hypnum turgescens*), now confined in temperate latitudes to the highest Alps. The latter grows in Herjedelen on the Dovrefield, in the north of Scandinavia, in Bear Island, Spitzbergen, and Greenland. The genial climate of the Pliocene period thus gradually passed away, and was succeeded by the glacial conditions of early Pleistocene times.

GENERAL CHARACTER OF CAINOZOIC FLORAS AND FAUNAS.

The floras of the Tertiary era were undoubtedly more luxuriant and more varied than that of modern Europe. Nothing is more remarkable than the assemblage within our continent of numerous forms whose nearest living allies are now widely scattered over the warmer regions of the globe—in Asia, Australia, Africa, America. The plants of early Tertiary times, although differing specifically and often generically from living forms, yet approach on the whole to existing types. Palms were a common feature of the Tertiary floras from Eocene into Pliocene times, but they had disappeared from Middle Europe before the close of the Pliocene. Indo-Australian types were common in Europe during the early Eocene, but later on forms characteristic of the warmer latitudes of North America began to abound. A commingling of Indo-Australian and

American types also marked the Oligocene period, but the American forms gradually increased until in Miocene times they came to preponderate over all the others. The Pliocene flora of Central Europe had a prevalent Mediterranean character. With regard to the lower forms of animal life in the Tertiary all that we need note here is the general fact that these have now a modern aspect, the number of living genera and species becoming greater as we advance from the lower to the higher stages. The foraminifers attained now their maximum development, and are characteristically represented by the large coin-shaped nummulite. Amongst the molluscs the cephalopods are no longer dominant forms—the most abundant groups being lamellibranchs and gasteropods, which occur in prodigious numbers. But the most characteristic forms were the mammals. These, as we have seen, made their first appearance early in the Mesozoic era in the form of diminutive marsupials. But in Eocene times they received a great development—many of the forms attaining a large size. Among the more characteristic types of the earlier European Tertiary are *Palæotherium* and *Anoplotherium*, along with which were carnivores, rodents, insectivores, and bats, also the earliest representatives of the horse and the monkey tribe. The later Tertiaries are marked by the appearance of dinotheres, mastodons, true elephants, rhinoceroses, hippopotamus, deer, antelopes, gazelles, various carnivores, such as *Machairodus*, bears, cats, wolves, etc., and apes. No certain or unequivocal evidence is yet forthcoming of the appearance of man. Some authors, however, maintain that man's handiwork is seen in certain stone "implements" obtained from Miocene strata in France and Portugal; others doubt whether the "implements" are really the work of man; while yet others deny that they were found in undisturbed strata. In the Pliocene of Italy bones, cut and scored by some sharp instrument, have been met with. The bones occur in undisturbed beds, and are believed by some geologists to have been cut by man; others, however, attribute the marks to the teeth or claws of some predaceous animal.

While it is true that the general aspect of the plant- and animal-life of the Cainozoic era approaches to that of the present, yet this is truer for the less highly organised types than it is for those which are higher in the scale of being. A collection of Tertiary shells and corals, for example, strikes us with its modern aspect—many of the species and a still larger number of the genera being living forms. Even the fishes have a modern facies, but with the higher vertebrates of the earlier Tertiary period it is very different. Several of these are intermediate types, that is to say, they possessed characters which are now met with in widely separated forms.

Thus some beasts of prey were allied partly to the marsupials and partly to the placental mammals. The *Arctocyon*, for example, was a carnivore with a marsupial-like brain. Then there were forms intermediate in character between the tapir-like palæotheres and the existing horse ; also types allied to hogs and carnivores. The appearance of many marsupials and the possession of marsupial characters by the carnivores are most noteworthy features in the early Tertiaries of Europe. In later times the marsupial element declined, and before the advent of the Pliocene it had entirely disappeared from the mammalian fauna of our continent.

EVOLUTION OF CONTINENTAL AREAS IN CAINOZOIC TIMES.

Before the Eocene beds began to be deposited, the bottom of the Cretaceous sea in Northern and Middle Europe had been extensively elevated, and those regions were never again so much submerged. The southern portions of the continent, however, were still largely under water, while great bays and arms of the sea extended now and again northwards from the Mediterranean area into Central Europe. On to the close of the Miocene period, indeed, Southern and South-eastern Europe consisted of a series of irregular peninsulas and islands washed by the waters of a genial sea. Towards the close of early Tertiary times the Alps, which had hitherto been of small importance, were greatly upheaved, as also were the Pyrenees and the Carpathians. The floor of the "Nummulitic sea" was pushed up many thousand feet, its deposits being folded, twisted, inverted, and metamorphosed. Another great elevation of the same area was effected after the Miocene period, the accumulations of that period now forming considerable mountains along the northern flanks of the Alpine chain. Many of the highest mountain-chains of the globe, in short, date their greatest elevation to the Cainozoic era. Thus Eocene strata occur in the Himalaya at a height of 16,500 feet, in the Alps of 10,000 feet, and in the Pyrenees at about the same elevation. Notwithstanding these gigantic upheavals in Central Europe, perhaps in consequence of them, the lower-lying tracts of what is now Southern Europe continued to be largely submerged, and even the middle regions of the Continent were now and again occupied by great lakes, which sometimes communicated with the sea. Thus in Miocene times an arm of the sea extended up the Rhone valley, and stretched across the north of Switzerland to the basin of the Danube. After the elevation of the Miocene, those inland stretches of sea disappeared, but the Mediterranean still overflowed wider areas in Southern

Europe than it does in our day. Eventually, however, in late Pliocene times, the bed of that sea experienced considerable elevation, the newer Pliocene strata of Sicily occurring now up to a height of 3000 feet at least. It was probably at the same time that the Black Sea and the Sea of Asov retreated from the wide low-grounds of Southern Russia, and that the inland seas and lakes of Austro-Hungary finally vanished.

The Tertiary era is distinguished in Europe for its volcanic phenomena. The grandest eruptions were those of Oligocene times. To that date belong the basalts of Antrim, Mull, Skye, and the Faeröe Islands, and probably also the older series of volcanic rocks in Iceland. These speak to us of prodigious fissure-eruptions, forming enormous plateaux, of which we now behold but the merest fragments. The ancient volcanoes of Auvergne, Velay, and Vivarais in France, are of Tertiary age, so likewise are the basalts, trachytes, phonolites, tuffs, and lake-filled Maars of the Eifel and the neighbourhood of the Laacher See, the volcanic rocks of the Siebengebirge, the Vogelsgebirge, and many other places in Germany. The volcanic rocks of Hungary and the Siebenbürgens are also well-known examples, while in the south of Europe, Etna, Vesuvius, and other Italian volcanoes, date their origin in like manner to Tertiary times.

The climatic conditions of the Cainozoic era were at first decidedly tropical (Eocene and Oligocene), becoming sub-tropical later on (Miocene), and eventually assuming a temperate character (Pliocene). The Palæozoic floras and faunas, as we have seen, seem to indicate that a genial equable climate extended over the globe—corals flourishing in the Arctic Seas just as they did in those of southern latitudes. In Mesozoic strata, however, we begin to find evidence of different climatic zones, the floras and faunas of southern regions being more abundant and varied than those of higher latitudes. These features are still more marked in the Cainozoic systems, particularly in the middle and later stages. Thus at a time when Italy was clothed with a tropical vegetation in which great palm-trees predominated, Middle Europe had its extensive forests of evergreens and conifers, while in the region of the Baltic conifers and deciduous trees were the prevailing forms. We know also that the floras of the low grounds differed to some extent from that of the hills and mountains. Towards the close of the Tertiary era a general lowering of the temperature took place, which eventually resulted in the extinction of many tribes of plants and animals.

CHAPTER XXV.

HISTORICAL GEOLOGY—POST-TERTIARY OR QUATERNARY SYSTEMS.

Pleistocene or Glacial system: life and physical conditions—Post-glacial and Recent system: life; physical conditions—Correlation of Archæological and Geological periods—Geographical conditions of Post-tertiary times—Climate of Post-tertiary times.

I.—PLEISTOCENE OR GLACIAL.

The deposits of the Post-Tertiary or Quaternary era are of very variable character, and are usually grouped into two systems—the Pleistocene or Glacial and the Post-glacial and Recent. With a few exceptions the molluscs occurring in these Post-tertiary formations all belong to existing species, the exceptions occurring only in the older division; which is termed Pleistocene or Glacial, according as we have reference to the character of its organic remains or to the physical conditions under which the greater portion of its deposits were accumulated. Although these deposits are of very diverse nature and origin, and are subject to endless modifications, they nevertheless show certain well-marked phases, which are persistent over vast regions. Thus throughout all Northern Europe and the hilly and mountainous districts in the central and southern regions of the Continent, they not only exhibit the same general character, but they present us likewise with the same general succession. In the low grounds outside of those areas, as in those of Southern England, France, Belgium, Spain and Portugal, Italy, etc., the Pleistocene deposits have quite another aspect. The following tables give the average general succession of the Pleistocene deposits in several typical regions.

(1) Region of Northern Europe.—The succession within the British area is very clearly displayed in Scotland, as follows:—

6. Valley-moraines and fluvio-glacial gravels = small local glaciers.

5. Kames, erratics, fluvio-glacial gravels, sands, and clays, all unfossiliferous = deposits laid down during the melting of a general ice-covering or mer de glace.
4. Clays, sands, etc., with Arctic marine shells and erratics, occurring up to a height of 100 feet above present sea-level = deposits belonging to the period of retreat of great mer de glace, and contemporaneous to a large extent with those of 5.
3. Upper boulder-clay or till: a tough unstratified clay, full of glaciated stones and boulders = moraine profonde of a mer de glace which covered all Scotland and overflowed the Outer Hebrides.
2. Interglacial beds of fresh-water and of marine origin = disappearance of mer de glace; clothing and peopling of land-surface with temperate flora and fauna (mammoth, horse, urus, Irish deer); subsequent submergence to a depth of probably not less than 500 feet below present sea-level.
1. Lower boulder-clay or till; an unstratified clay, full of glaciated stones and boulders; somewhat harder and tougher on the whole than the upper till; contains intercalated layers of laminated clay, sand, and gravel (usually more or less confused, crumpled, or contorted), which indicate the former presence of a subglacial water-drainage. The lower boulder-clay marks the epoch of greatest glaciation; Scotland and all its islands drowned in ice, which was confluent with that of Scandinavia.

In England and Ireland the succession is essentially similar, with this exception that these regions do not appear to have any well-marked representative of the 100 feet marine terrace of Scotland:—

6. Valley moraines and fluvio-glacial gravels.
5 and 4. Kames or eskers, erratics; fluvio-glacial deposits.
3. Upper boulder-clay = moraine profonde of latest mer de glace.
2. Middle sands and gravels with marine shells. Near Hull these beds are of shallow-water origin, and have yielded remains of the Pleistocene mammals. Disappearance of glacial conditions; land-surface at first; subsequent submergence to an undetermined extent, but probably several hundred feet.
1. Lower boulder-clays, with intercalations of sand, gravel, etc., which appear to have the same significance as the stratified beds in the lower till of Scotland.

In Scandinavia, Denmark, Holland, North Germany, etc., similar series of glacial and interglacial accumulations occur, with this exception that these last are chiefly of fresh-water origin. The succession in Mark Brandenburg may be taken as a type :—

4. Sand and gravel, with erratics. (Kames and fluvio-glacial deposits.)
3. Upper boulder clay = moraine profonde of latest mer de glace.
2. Sand and gravel with remains of mammoth, woolly rhinoceros, urus, reindeer, bear, etc., and fresh-water shells.
1. Lower boulder clay, overlying in places, gravel and sand.

(2) Region of Central and Southern Europe.—Near Dürnten in Switzerland we have the following succession, which, it will be seen, agrees essentially with those already given from Northern Europe :—

3. Morainic sand and gravel with large erratics.
2. Sand and gravel with thick lignite, and mammalian remains, such as elephant, mammoth, rhinoceros, urus, deer, bear, etc.
1. Boulder-clay or ground-moraine.

Elsewhere in Switzerland, Bavaria, and Northern Italy, a similar succession appears, in some places interglacial deposits occurring at two and even three levels in one and the sames series. Again, at Mont Perrier, near Issoire in France, we have the following succession :—

3. Moraines of glacier flowing from Mont Dore.
2. Interglacial beds with plants indicative of a genial climate, and such mammals as southern elephant, hippopotamus, rhinoceros, hyæna, horse, deer, etc.
1. Moraine profonde of glaciers from Mont Dore.

(3) Regions outside of Glaciated Areas.—The Pleistocene deposits in those regions are represented principally by sheets of clay and earthy matter with angular stones, breccias, fluviatile gravels, etc., calcareous tufa, peat, and cave-accumulations. The sheets of rock-rubbish, etc., are known in the south of England as "Head," in France they are termed "Red Diluvium ;" the great limestone-breccias of Gibraltar are of the same nature. The fluviatile deposits consist of gravel and loam. The gravels are confined chiefly to the valleys, but occur at all levels, and have yielded a large number of remains of extinct or emigrated mammals together with those of animals which are still indigenous. They are further noteworthy for the numerous flint implements which

have been obtained from them. Very frequently these gravels are overlaid by sheets of a fine loam called löss, which often clothes the slopes of the valleys and the surfaces of the plateaux between contiguous valleys. Human relics and mammalian remains are often encountered in it—the remains consisting chiefly of species from Alpine and northern or cold-temperate regions. From the tufas and peat abundant relics of the Pleistocene flora have been obtained, while the caves have yielded a great harvest of mammalian remains and human relics.

It is thus evident that the Pleistocene deposits which occur in regions lying beyond the reach of glaciation have quite a different aspect from the accumulations which are encountered in the Alps, the Pyrenees, etc., or in Northern Europe. Nevertheless, they are closely related to these, and indeed some of the deposits of such regions as the south of England and north of France may fairly be looked upon as glacial accumulations.

(1) Glacial and Fluvio-glacial Deposits.

Northern Europe.—The general distribution and origin of the stony clays have been discussed in chapter vii. It was there shown that the till or boulder-clay of Northern Europe is the ground- or bottom-moraine of an ice-sheet or mer de glace which overwhelmed a large portion of our continent; while the similar stony clay of the Alpine lands of Middle and Southern Europe is in like manner the moraine profonde of gigantic glaciers, which are represented now by puny shrunken ice-streams confined to a few of the higher valleys of the Alps, etc. In Northern Europe the boulder-clay often overlies wide sheets of sand and gravel which appear to be of the nature of fluvio-glacial deposits, formed by the waters that escaped from the ice during its advance. The direction followed by the ice is indicated by the trend of the striæ on the rocks, by the position of roches moutonnées, and by the "carry" of the stones and boulders. Thus we learn that the great mer de glace radiated from the high grounds of Scandinavia northward into the Arctic Sea, east and south-east into Russia, south into Germany, south-west into Holland and the borders of Belgium. In the British area the ice likewise radiated from the dominant high grounds, but its course was modified by various causes. Thus the ice that streamed into the Central Lowlands of Scotland from the Highlands and Southern Uplands united to form a mer de glace which flowed east into the area of the North Sea, and west and south-west by the Firth of Clyde on its way to the Atlantic. Again, the ice that flowed out into the North Sea from Scotland and the north of

England met and coalesced with the great Scandinavian mer de glace, the pressure of which forced the British mer de glace in two directions —one branch going north and subsequently sweeping across the Orkney and Shetland Islands, and another passing southward until the increasing pressure of the advancing Scandinavian ice forced the general ice-flow across the Midlands of England to the valley of the Severn. With the exception of the tops of the highest mountains and a narrow strip of land in the extreme south of England all the British Islands may be said to have been drowned in one continuous mer de glace which filled up the shallow seas that now wash our shores. In the extreme north-west the Outer Hebrides were overwhelmed by the ice-flow coming from the Highlands, and in like manner the islands lying off the west coast of Ireland were invaded and buried under the ice that made its way from that country towards the Atlantic. The basin of the Irish Sea, again, was occupied by ice flowing from Ireland, Scotland, and England—the united mass streaming south and south-west into the same ocean, where doubtless it terminated in a perpendicular wall like the great ice-wall of the Antarctic Circle. Thus all Northern Europe was obliterated under one and the same continuous mer de glace—above the surface of which only the tops of the higher mountains of Scandinavia and Britain protruded, like so many islets. From beyond the west of Ireland this great sea of ice extended over 70 degrees of longitude eastwards to the valley of the Petchora and the foot of the Ural Mountains, while from north to south it covered all the regions lying between the North Cape and the hills of Middle Germany, or more than 20 degrees of latitude.

The moraine profonde (till or boulder-clay) of this enormous ice-sheet attains its greatest thickness (more than 100 feet) on the lower-lying tracts, which it often covers continuously for hundreds of square miles. Followed towards the mountains it becomes thinner and less continuous, and is largely confined to the valleys, in which it is often arranged as a series of long mounds or "drums," which trend in the same direction as the ice-flow. It appears scattered over the surface of high plateaux, and nestles in hollows behind prominent crags and hills up to heights of several thousand feet. At the highest elevations it is represented by a rubble of angular, sub-angular, and glaciated stones and boulders. The rock-surface under the till is often much smoothed, polished, and covered with rectilinear striæ; not infrequently, however, it is highly smashed and shattered, and the broken débris is involved in the lower portion of the till. Occasionally the underlying rocks are highly contorted, fissured, dislocated, and displaced, as in Moen (Denmark), where the disturbances of the Chalk were at one time believed to

be the result of subterranean action. Similar extraordinary displacements of strata occur at many other places in the low grounds of Northern Germany. Huge pot-holes called giants' kettles, filled with waterworn stones and boulders (see fig. 23, p. 58), also appear now and again underneath the boulder-clay. Another common phenomenon in glaciated regions is that of "crag and tail;" familiar examples of which are met with all over the Lowlands of Scotland. Many of the mountainous islands lying off the west coast of that country exhibit the same phenomenon on a larger scale. Deep crescent-shaped hollows have been dug out in the sea-bottom in front of those islands by the ice advancing from the mainland, while in the rear a long "tail" extends in the direction of ice-flow. The islands of Arran, Eigg, Rum, and others off the Scottish coast, and Rathlin off that of Ireland, are good examples. The general effects produced by the northern mer de glace are now conspicuously seen in the rounded and flowing outlines of hill and valley. This appearance is most conspicuous when we view a landscape in the direction followed by the ice. Up to a certain height the hill-tops are smoothed and moutonnée, while at higher elevations they appear harsh and rugged. These rougher heights are the portions which rose above the level of the mer de glace and escaped glaciation. In the Outer Hebrides they appear at an elevation of 1600 feet, on the Scottish mainland of 3000 feet, in Norway of 7000 feet or thereabout. Another effect of the ice-sheet was the removal of the loose weathered rock-surfaces which must have existed before the advent of the Glacial period. In all the glaciated countries of Europe there is a general absence of those thick sheets of "weathered rock" which are so conspicuous a feature of regions which have not been subjected to glacial action (see p. 13).

Central and Southern Europe.—In chapter vii. some account has been given of the ancient glaciers of Central and Southern Europe. It is difficult to realise the extent of the ice-flows that escaped from the Alps and other mountains to deploy upon the low grounds at their base. The old glacier of the Rhone not only covered all the area now occupied by Lake Geneva, but reached to a height of nearly 4000 feet on the slopes of the Jura. In some places, indeed, it even overflowed through passes in those mountains at a height of over 3000 feet, sending long streams of ice through the French Jura to the low grounds beyond. The main trunk of the Rhone glacier made its way out of Switzerland and flowed far into the plains of France, where it coalesced with similar large glaciers that streamed outwards from the mountains of Savoy and Dauphiny. The moraines of these enormous flows may be followed as far south as Lyons and Vienne. In like manner all

the valleys that open north from the Alps and the Tyrol were filled with great glaciers, which spread themselves far out upon the low grounds of Baden, Hohenzollern, Würtemberg, Upper Swabia, and over wide areas in Upper Bavaria and Upper Austria. Enormous ice-streams at the same time occupied all the main valleys on the southern side of the Alps, and, descending to the plains of Piedmont, Lombardy, and Venetia, piled up huge moraines, some of which would in this country pass for considerable hills. Similar phenomena appear in all the other mountain-tracts of Central and Southern Europe—considerable snow-fields and glaciers having existed in many regions which are now far below the snow-line. The Black Forest, the Vosges, the Central Plateau of France, the Pyrenees and the Spanish Sierras, Corsica, the Apuan Alps and Apennines, the Despoto Dagh, etc., had each their snow-fields and glaciers. The evidence for the former existence of such are glacial striæ, roches moutonnées, boulder-clay (moraine profonde), terminal and lateral moraines, perched blocks, etc.

Rock-Débris; Breccias; Head, etc.—Outside of such glaciated tracts there occur in many places enormous accumulations of rock-rubbish or débris, sometimes compacted into breccia, which appear to have been due to the action of frost. These breccias, etc., occur in regions where the conditions under which they were formed do not now obtain, as, for example, at Gibraltar and other localities in the south of Europe. In Northern France and the south of England sheets of similar earthy rock-rubbish (called "head") are spread over the low grounds in many places. The rubbish-heaps referred to have evidently travelled forward over gently-sloping surfaces for considerable distances. There are no heights from which the stones could have rolled, and it is obvious that the accumulations are not now accreting, but are being denuded and worn away by sub-aërial agencies. These remarkable masses have been formed under severe climatic conditions, the rocks having been detached and shattered into fragments by frost. In summer time such masses would be saturated with water from melting snow and ice, and compelled to flow forward like the water-saturated "earth-glaciers" of the Rocky Mountains. Thus while an enormous ice-sheet covered Northern Europe, and great glaciers were descending from all the mountains in the central and southern regions of the Continent, severe conditions of climate also obtained at much lower levels outside of the glaciated areas. Frost broke and shattered the rocks in the low grounds of Southern England and Northern France, and the surface of such tracts was littered with débris and earthy rubbish. Farther south the rock-rubbish only formed at considerable heights from which it gradually travelled downwards.

Fluvio-Glacial Deposits, Löss, etc.—At the same time the rivers escaping from the northern mer de glace and the glaciated regions of the Alps, etc., carried forwards immense quantities of shingle and gravel, with which they cumbered their valleys. Such *fluvio-glacial* deposits are a common feature of all the great valleys that head in mountains where extensive snow-fields and glaciers formerly existed. The rivers of the period must have been extremely muddy—the fine silts and loams of the period covering enormous tracts of country, especially in the valleys of the Rhine, the Rhone, the Danube, and their tributaries. Some of those fine-grained fluvio-glacial accumulations occur at heights and in positions which it is hardly possible the rivers could have reached unless their valleys had been partially filled up or dammed. Darwin has suggested that this might have been the case—that during winter when the rivers were greatly reduced in volume and even frozen over, snow might have been blown into the valleys, from which it might not have been entirely removed in summer. This filling-up, repeated winter after winter, might thus eventually have the effect of partially damming the waters, and compelling them to rise to levels and overflow wide tracts which they could not otherwise have attained. Such it is supposed may have been the origin of the high-level löss of the Rhine and many other valleys in Middle and Western Europe. Again the muddy rivers flowing north would be dammed back by the great mer de glace, and thus a wide belt of low ground would be converted into a glacial lake, over the bed of which the löss of Belgium, etc., might have accumulated. Another enormous tract of löss occurs in Southern Russia: this is the well-known Black-earth (Tchernozem). There is reason to believe, however, that the löss has been largely re-arranged by wind-action. It contains remains of jerboa, marmot, lemming, etc. —a fauna indicative of steppe-conditions.

Moraines, Erratics, Kames, etc.—The gradual disappearance of the northern mer de glace, and the retreat of the valley-glaciers of Central and Southern Europe, was marked by the piling-up of huge moraines, the strewing of erratics, and the deposition of great sheets of fluvio-glacial detritus, gravel, sand, and silt. The terminal moraines of the ice-sheet consist largely of banks, ridges, and hillocks of coarse shingle, gravel, and sand, with which large and small erratics are frequently associated. The great moraines accumulated by the Alpine glaciers in the low grounds are also made up principally of water-worn detritus commingled with angular erratics. Much of this material no doubt was derived from the denudation of superficial moraines, and carried down by water flowing over the surface of the ice. Such gravelly moraines (kames) are well developed

in Scotland, especially opposite the mouths of the mountain-valleys. They often pass laterally into sheets of gravel, sand, and loamy silt and clay. Other long mounds and ridges of gravel and sand, which occur in the low grounds of the British Islands and Scandinavia,

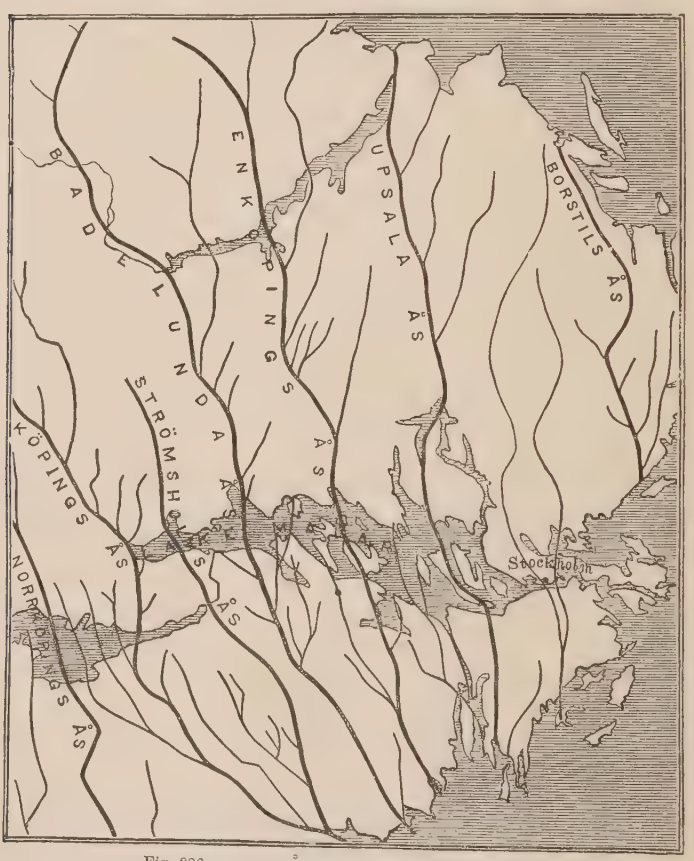


Fig. 386.—MAP OF ÅSAR IN BASIN OF LAKE MÄLAR.
(Upsala Ås is nearly 124 miles long; Enköpings Ås, 210 miles.)

appear to have had a different origin, and to have been formed by rivers and torrents flowing underneath the ice—by sub-glacial waters, in short. Ridges of this kind are best developed in Southern Sweden, where they often run continuously for more than

100 miles—sometimes one dominant ridge being joined by many tributary ridges, just as a river by its affluents (fig. 386). Such gravelly and sandy ridges or embankments, in whatsoever way formed, are now generally termed *eskers*. The Swedish ridges (*åsar*), and certain of our own kames, are not the only evidence of sub-glacial drainage, for the till itself often contains irregular and interrupted beds of water-worn materials which are curiously contorted, confused, and involved. Evidently such inclusions point to old temporary water-channels or tunnels under the ice, which had collapsed while the mer de glace was flowing.

(2) Interglacial Deposits.

The till is not one continuous accumulation from bottom to top. In reality there are more than one bed or sheet of till. This is shown by the occurrence of intercalated beds containing sometimes marine and sometimes fresh-water and terrestrial organisms. These remarkable interglacial deposits occur in almost every glaciated region where they have been looked for. They consist of gravel, sand, or clay, and sometimes also of peat or lignite. From the interglacial fresh-water deposits of Northern Europe have been obtained the remains of such mammals as *Elephas primigenius* (mammoth), *E. antiquus*, *Rhinoceros tichorhinus* (woolly rhinoceros), *Cervus tarandus* (reindeer), *C. elaphus* (red-deer), *C. megaceros* (Irish deer), *C. euryceros*, *C. alces* (elk), *Ovibos moschatus* (musk sheep), *Bos. sp.*, *Bos primigenius* (urus), horse, bear, etc. Amongst the fresh-water molluscs are *Paludina diluviana*, *P. vivipara*, *Valvata piscinalis*, *Bythinia tentaculata*, *Limnæa auricularia*, *L. truncatula*, *Planorbis marginatus*, *Sphærium solidum*, *Pisidium amnicum*, *Unio*, *Cyrena fluminalis*, etc. Plants are represented by *Dryas octopetala*, *Betula nana*, and *Salix polaris*, and also by alder, maple, oak, willow, hornbeam, lime, birch, hazel, water-chestnut, dogwood, Scots fir, spruce, larch, *Geranium columbinum*, and several herbaceous plants, grasses, etc. At various places in Prussia layers of diatomaceous earth are likewise met with between lower and overlying boulder-clays. Interglacial deposits occur only here and there, and are rarely continuous for any distance. They are often contorted and crumpled, and are evidently mere wrecks of former more extensive accumulations. Their occurrence shows us that the great northern mer de glace occasionally disappeared, while plants and animals clothed and peopled the lands vacated by it. The organic remains mentioned above are partly of Arctic and northern habitats, while others are

decidedly temperate species. The presence of the latter therefore in interglacial deposits is indicative of great climatic changes. When oaks, birches, maples, and limes were growing in Northern Germany, and oaks and birches in Central Scotland, it is evident that the climate of Northern Europe could hardly have been less temperate than it is to-day. The occurrence of Irish deer, stag, horse, urus, and elephant (*E. antiquus*) is further evidence in the same direction. The northern and Arctic forms doubtless occupied the same ground when the climate had deteriorated. In short, the evidence of both plants and animals points to secular changes of climate during the Glacial period, and to consequent secular migrations of faunas and floras.

Now and again the stratified deposits between the boulder-clays of Northern Europe contain marine shells—some of which are northern and Arctic species, such as *Pecten islandicus*, *Leda truncata*, *L. lanceolata* (*Yoldia arctica*), *Astarte borealis*, *Mya truncata*, etc., while others are living British species. The presence of such marine beds, if occurring in undisturbed positions, is good proof that the regions in which they occur have been submerged. Many appearances, however, lead to the belief that some of the fossiliferous deposits, associated with shelly boulder-clays, may have been derived from these by the action of fluvio-glacial waters.[1] In Norway marine beds with Arctic shells go up to a height of 640 to 700 feet, but these may be of later date than the interglacial marine beds now under consideration. Some of the ancient sea-margins (strandlinier) of that country, however, appear to be of interglacial age. These strandlinier are horizontal terraces excavated in rock by the action of the sea, and some of them seem to have been subsequently glaciated by land-ice. In Scotland traces of similar rock-terraces have been met with at a height of two or three hundred feet above the sea, which are clearly older than the latest advance of the general mer de glace, since they are both glaciated and sprinkled with boulder-clay. Marine interglacial beds usually, but certainly not always, attain a greater

[1] Some boulder-clays contain marine shells, both whole and broken, but these are derivative—they are erratics just as much as the stones with which they are associated: sometimes indeed they are striated. Such boulder-clays are usually met with in regions which have been over-ridden by ice advancing upon them from the sea. Thus the till in the north of the Lewis is shelly—the shells having been derived from the bottom of the Minch by the ice flowing out from the mainland. Shells of Pliocene species occur in the boulder-clay near Como in Italy; and Miocene, Pliocene, and Recent species are likewise met with in the moraine de fond of the Rhone glacier near Lyons. In these cases the shells have evidently been derived from pre-existing deposits, which the glaciers demolished during their advance. A shelly boulder-clay cannot therefore be taken as evidence of submergence.

thickness than the fresh-water layers that are intercalated between the boulder-clays. They are well developed in Cheshire, Lancashire, etc.

Interglacial deposits exclusively of fresh-water and terrestrial origin occur also in the glaciated tracts of Central Europe. In Switzerland these deposits contain lignites which have yielded traces of an abundant flora resembling that which now clothes the low grounds of that country. Associated with that flora occur the remains of elephant (*E. antiquus*), mammoth, woolly rhinoceros, *Rhinoceros Merckii*, urus, elk, red-deer, and cave-bear. Similar lignites appear between boulder-clays in Upper Bavaria, and they are likewise met with on the Italian side of the Alps, where they indicate for the lower reaches of the mountain-valleys a climate as warm as that of the plains of Lombardy and Venetia. The associated mammalian remains include the southern elephant (*Elephas meridionalis*), rhinoceros (not *R. tichorhinus*), beaver, deer, etc. The interglacial deposits of Central France tell a like tale of genial conditions. That region was then clothed with forests of elm, oak, hornbeam, box, etc., and had for its occupants the southern elephant, rhinoceros, hippopotamus, horse, cave-bear, hyæna, deer, etc. The deposits containing the relics of that flora and fauna rest upon and are covered by glacial moraines. Thus the glacial accumulations of Central Europe are equally eloquent of great climatic changes during the Glacial period.

(3) Fluviatile, etc., Deposits in Regions Outside of Glaciated Areas.

Löss.—The löss is a fluvio-glacial deposit modified by æolian action. It has yielded many organic remains. These consist for the most part of terrestrial shells such as many species of *Helix*, *Pupa*, *Succinea*, etc., and here and there some fresh-water forms—the general facies of the molluscs indicating colder and drier climatic conditions than now characterise the regions where it occurs. The same inference may be drawn from the mammalian fauna, which includes such forms as mammoth, woolly rhinoceros, reindeer, glutton, lemming, marmot, pouched marmot, jerboa, horse, hyæna, cave-bear, urus, bison, etc. Human bones and relics also occur.

River Alluvia, etc.—The Pleistocene fresh-water deposits which occur in regions outside of the glaciated areas contain the relics of strongly contrasted faunas and floras. They are typically represented by the old valley gravels of the Thames and other streams in the south of England, and by those of the Seine, the Somme, and other rivers in the north of France. They occur at low and

high levels in the valleys, but no strongly-marked line can be drawn between the two series. Overlying both series comes very frequently an accumulation of loam or löss. Implements of human manufacture occur in these gravels at all levels. They consist of rudely-chipped flints belonging to the *Palæolithic* type of archæologists (fig. 397). Associated with such implements in undisturbed strata occur the remains of numerous mammalian animals of southern, temperate, and northern forms — the southern forms being most commonly met with in the low-level beds, while the northern forms are most characteristic of the high-level gravels.

Calcareous Tufa, Peat, etc. — Here and there deposits of calcareous tufa occur, from which many relics of the Pleistocene flora have been obtained. And similar plant-remains have now and again been obtained from peat and lacustrine deposits belonging to the same period.

Cave Accumulations. — These have yielded numerous remains of palæolithic man and the animals with which he was contemporary. The appearances presented by such accumulations are extremely variable. Very frequently the floor of a cave when dug into presents a succession of deposits of reddish earths, separated from each other by more or less continuous sheets of stalagmite. At the very surface there may be a darkish earth in which may occur human relics of no great antiquity — ancient British or Roman or even much more modern remains. Along with these any mammalian bones that may occur will belong to recent indigenous species. Underneath this superficial layer, however, comes a sheet of stalagmite, as a rule, in and below which relics and remains of a totally different kind are encountered. This stalagmite may be succeeded downwards by layers of reddish earth and other stalagmitic pavements, all of which may yield organic remains. These organic remains comprise a number of mammals, consisting in some cases of northern species, in other cases of southern and temperate types. Human relics often accompany the mammalian remains, such as implements and ornaments of bone and flint, burnt bones, charcoal, etc. Many caves, indeed have been occupied sometimes by man, sometimes by beasts of prey; and the relics of human and bestial repasts often abound. It is important to note that a break in the succession always occurs between the uppermost layer containing remains of palæolithic man and his contemporaries, and the overlying superficial layer with more recent relics. The mammalian fauna with which palæolithic man was associated embraced a number of extinct or no longer indigenous species; the fauna that succeeded is the same as that which characterises Europe at the present day.

Organic Remains in Fluviatile, etc., Deposits.—The plants met with in the various deposits referred to in preceding paragraphs consist of numerous forms which indicate a genial and equable climate, while others point as conclusively to cold and even Arctic conditions. Thus Tuscany, Northern France, and Germany were clothed with forests during some part of the Pleistocene period, the general assemblage of plants betokening for those regions a more humid and equable climate than they now enjoy. In the north of France grew willows, hazels, ash, dwarf elder, sycamore, spindle trees, perfumed cherry tree, box, clematis, common ivy, judas tree, fig-tree, Canary laurel, etc. The presence of the Canary laurel, which flowers in winter, shows us that the winters must have been mild, and the evidence of the other plants points to a genial humid climate. The summers were not so hot and dry as they now are in France, and the winters were not so cold; and similar conditions obtained in Central Germany and the Mediterranean area—although the floras of those different zones were distinguished from each other by the presence of certain forms and the absence of others. From other Pleistocene deposits in the same latitudes we get the relics of a very different flora. At low levels in Northern France, for example, grew birch, alder, larch, spruce, juniper, and yew; in the low grounds of Switzerland flourished the dwarf birch, the Arctic willow, and northern and high-alpine species of mosses; and in Northern Germany a similar Arctic flora prevailed. In Northern Italy, again, the Cembran pine grew so low down as Ivrea, and the Scots fir, which nowadays is wellnigh restricted to dry localities in the Alps, ranging between 300 and 2000 metres of elevation, flourished upon the shores of Lake Varese.

The fresh-water and terrestrial molluscs tell a similar tale of discordant climatic conditions, some deposits containing shells whose general facies is indicative of genial conditions, while in certain other accumulations the molluscs are all high-alpine and northern forms. As far south as Corsica we have evidence of a wet and ungenial climate; as far north as Northern France and Southern England we meet with proofs of genial and equable climatic conditions.

The mammals of the Pleistocene may be grouped as follows:—

Southern group, comprising species that are now living in latitudes south of the Black Sea and the Mediterranean area, namely, hippopotamus, African elephant, spotted hyæna, striped hyæna, serval, Caffer cat, lion, leopard, various extinct species of elephant and rhinoceros, and the extinct dwarf hippopotamus and *Machairodus*.

Temperate group: comprising species characteristic of temperate

latitudes, such as urus, bison, horse, stag, roe, saiga, beaver, hare, rabbit, otter, stoat, weasel, martin, wild cat, fox, wild boar, brown bear, grisly bear, and the extinct Irish deer and cave-bear.

Northern and Alpine group: comprising species confined to northern latitudes or mountain-ranges where similar climatic conditions obtain, namely, musk-sheep, glutton, reindeer, Arctic fox, lemming, tailless hare, Alpine hare, marmot, pouched marmot, ibex, snowy vole, chamoix, and the extinct mammoth and woolly rhinoceros.

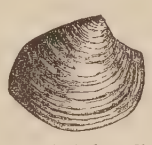
It is evident that all these animals could not possibly have lived side by side in the same region. Their occurrence in the Pleistocene indicates great secular changes of climate. During severe conditions the reindeer and its associates swarmed in Southern France, where they were hunted by palæolithic man, while the denizens of the high Alps descended to the coast-lands of the Mediterranean, which were frequented at the same time by the glutton. When genial and equable conditions prevailed the northern and Alpine forms retreated, and their places were occupied by the southern and temperate species,—hippopotamus, elephant, rhinoceros, Irish deer, cave-bear, etc., roaming far north into what are now temperate latitudes.

The Pleistocene accumulations which occur outside of the glaciated areas have thus the same story to tell as the glacial and interglacial deposits already described. The former, in short, are the equivalents of the latter. This conclusion is borne out by the geographical distribution of the fossiliferous deposits just described. These occur at the surface only in those regions which were not overflowed by ice or fluvio-glacial waters during the latest great development of glacial action in Europe. Within the glaciated areas they are either wanting, or if they do occur it is in caves or as interglacial beds underlying the youngest boulder-clays. In a word, Pleistocene ossiferous gravels do not occur at the surface in Scotland, Ireland, Northern England and Wales, Scandinavia, Denmark, Northern Germany, etc., simply because they were swept away from those regions and demolished by the last incursion of the great mer de glace. And they are absent in like manner from the Alpine valleys of Central and Southern Europe for similar reasons. Although they have been eagerly sought for they have never yet been found overlying any glacial or fluvio-glacial deposit pertaining to the close of the Glacial period. On the contrary, there are few of the Pleistocene river-gravels which are not themselves overlaid by the flood-loams (löss) laid down during the last cold phase of the Ice age.

(4) Late Glacial Deposits.[1]

The deposits classed under this head consist of fluvio-glacial gravels, morainic gravels and moraines, glacial-lake terraces, and also, in some regions, of marine clays, sands, etc. When the ice made its final retreat from the low grounds of Northern Europe it left the ground cumbered with water-worn materials, erratics,

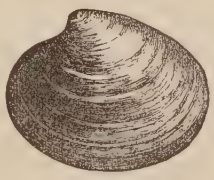
387. Mya truncata.



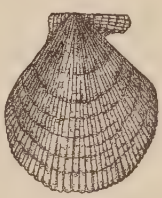
388. Astarte borealis

389. Saxicava rugosa.

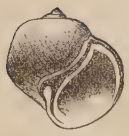
390. Buccinum undatum.



391. Cyprina islandica.



392. Pecten islandicus.



393. Natica clausa.

394. Turritella terebra.

395. Aporrhais pes-pelicani.

396. Scalaria grœnlandica.

Figs. 387 to 396.—FOSSILS FROM THE GLACIAL MARINE CLAYS (CLYDE BEDS, SCOTLAND).

morainic débris, etc., and the same kind of accumulations marked the retreat of the great glaciers of the Alps, etc. In Scotland, Scandinavia, and Northern Russia, some degree of submergence

[1] Characteristic fossils of the marine clays (glacial) of the Clyde, Scotland, are shown in the figs. 387 to 396. Some of these clays, however, probably belong to an earlier stage (see p. 378).

accompanied or followed the disappearance of the ice-sheet; and marine clays containing Arctic shells and ice-floated erratics were accumulated over the drowned areas. In Scotland the depression did not much exceed 100 feet below the present sea level—the late glacial marine clays forming what is known as the 100 feet terrace along the margins of the large estuaries. Followed inland those terraces merge into fluvio-glacial gravels, and these last when traced up the valleys are found to be associated with a succession of terminal moraines, which mark the various pauses made by the local or valley-glaciers during their final retreat. Thus the latest phase of the Ice age was one of cold climatic conditions; when these finally passed away the Pleistocene or Glacial period came to a close.

Pleistocene in other Continents.—The glacial and interglacial conditions which characterised Europe during the Pleistocene period were equally characteristic of North America. In that continent deposits of the same character and showing the same succession as those of Europe are encountered. A vast mer de glace covered all the northern regions and extended south to New Jersey, Ohio, Illinois, etc., reaching as far south in Missouri as the 38th parallel. Enormous glaciers at the same time descended the valleys of the Rocky Mountains to deploy upon the low grounds. In the Sierra Nevada, the Sierra Madre of Mexico, and in much less considerable hilly tracts, snowfields and glaciers likewise existed. Interglacial deposits have frequently been met with, the evidence they supply as to climatic changes being of the same kind as that which we meet with in Europe. In America, as in Europe, it is also evident that the last mer de glace was not so extensive as its predecessor. The terminal moraines of this last ice-sheet are among the most conspicuous of all the glacial accumulations of North America. In South America the proofs of a former greater intensity of cold are confined chiefly to the mountain-regions. They have been noted in many parts of the Cordillera, but in the extreme south (Fuegia) ice seems to have overflowed much of the low grounds. The Pleistocene fauna of North America embraces a somewhat different assemblage of animals from that of the corresponding deposits in Europe. Some of the more conspicuous forms were *Mastodon*, a true elephant (*E. Americanus*), horses (much larger than existing species), species of ox, bison, tapir, beaver, peccary, bear, lion, racoon; also extinct forms of the sloth family, such as *Megatherium*, *Mylodon*, *Megalonyx*. In South America the pampa deposits have yielded a large number of remains of gigantic sloths (*Megatherium*, *Megalonyx*), and armadillos

(*Glyptodon*), besides other mammalia. Traces of former snowfields and glaciers have been noted in Central Africa, in Kilimanjaro and Mount Kenia; and considerable ice-streams seem at one time to have existed in the valleys of the Atlas. New Zealand and Australia appear in like manner to have had their Glacial period; and the same seems to have been the case with some of the Chinese mountain-ranges as well as with the Himalaya, in whose valleys may be noted the moraines of gigantic extinct glaciers.

Life and Physical Conditions of the Period. — The general character of the Pleistocene floras and faunas has already been sufficiently illustrated. We may note here, however, the varied character of the interglacial flora and fauna. This flora recalls that of Pliocene times, and evidently betokens more genial and equable conditions than now obtain in the temperate latitudes of Europe. The mammalian fauna was also more varied, and embraced a much larger number of species than the present, and many of these attained a larger size than those of our day. This feature characterised not only the European mammals but those of other quarters of the globe as well. In Europe the Pleistocene was marked by great oscillations of climate — epochs of intense glacial or Arctic conditions, alternating with periods of genial and equable conditions. The Pleistocene was thus distinguished by great secular migrations of the flora and fauna, which eventually resulted in the extinction of numerous forms, and in the banishment of many more. It is in the accumulations of the Pleistocene that we meet with the first unquestioned relics of man. All these pertain to the Palæolithic phase, and consist of rudely-fashioned implements of flint and bone, but they include also some remarkable drawings or etchings on bones, reindeer antlers, etc., which have evidently been executed with the sharp point of a flint tool (see figs. 398, 399). Human bones are also met with, but they are not common. Flint implements occur underneath boulder-clay in East Anglia, so that Palæolithic man was a native of Europe before the climax of the Glacial period. No Palæolithic relics, however, are encountered in any deposits of younger age than the late glacial accumulations, those, namely, which were laid down during the last cold phase of the Pleistocene or Glacial period. In Europe Palæolithic man is eminently Pleistocene: before the advent of the Post-glacial and Recent period he had disappeared. The Palæolithic age, therefore, came to an end with the glacial and Arctic conditions that marked the close of the Pleistocene period.

II.—POST-GLACIAL AND RECENT.

The Post-glacial deposits contain the record of the changes which followed upon the disappearance of the last cold phase of the Glacial period. When these deposits occur within the glaciated areas they are found overlying the Late Glacial accumulations, and it is not difficult in such cases to distinguish them. Looked at broadly, the Post-glacial and Recent deposits are characterised by the presence of a flora and fauna not differing essentially from those of the present —there is an almost complete absence of the extinct or no longer indigenous mammals, only two of which survived in Europe the close of the Glacial period. Moreover, no trace of Palæolithic man or his relics has yet been found in any Post-glacial accumulation—the earliest human relics occurring in such deposits consisting of Neolithic implements (see fig. 400).

The Post-glacial and Recent accumulations consist of more or less loose incoherent deposits, which, like those of the Pleistocene, have been formed under very diverse conditions.

Lacustrine and Fluviatile Deposits.—The low-lying flats of alluvium which represent silted-up lakes, and those which appear in the bottoms of valleys at moderate elevations above the streams and rivers, are necessarily the most widely distributed of all the Post-glacial and Recent accumulations.

Bogs or Peat Mosses.—Most of the bogs of Northern and Central Europe belong to Post-glacial and Recent times, but some commenced to grow towards the close of the Glacial period. Many bogs overlie the remains of old forests; and not infrequently trees, occupying the place of growth, occur in the peat at various levels. Two such "buried forests" have been met with in the bogs over a wide region in North-western Europe. Round the coasts of Great Britain and Ireland and the opposite coasts of the Continent peat with buried trees passes out to sea, and has been dredged-up at considerable distances from the land.

Raised Beaches and Estuarine Flats.—These are terraces of gravel, sand, etc., containing marine and estuarine organic remains, which occur at various levels above the present sea-level. Occasionally the beaches consist of shelves or ledges excavated in solid rock by the waves and breakers, and very often these are backed by inland cliffs, in the lower part of which old sea-worn caves occur.

Moraines and Fluvio-glacial Gravels.—In the higher valleys of the Highlands many perfect moraines are of Post-glacial age—some of these moraines come down to the level of the 45-50 feet raised-beach. To the same age belong many high-level terraces of river gravels and loams.

Life of the Period.—Although the flora and fauna are essentially the same as at present, yet in some respects there were considerable differences. Thus, in the earlier stages of the period, the flora of North Germany, Denmark, and Scania was Arctic-alpine. The cold of the Glacial period was then passing away, and the Scandinavian flora was slowly returning northwards. This Arctic-alpine flora was accompanied by the northern mammals, particularly the reindeer. Later on in the period the Scandinavian flora and the northern fauna had disappeared from the low grounds of temperate Europe, and the present plants and animals had taken their place. Neolithic man does not appear to have entered Europe until the climate of our latitude had become temperate. Later on came the tribes who used bronze, and these were eventually succeeded by races who employed iron for their cutting implements and weapons. The Irish deer, and probably the mammoth, survived in Europe into Post-glacial times.

Physical Conditions.—After the final disappearance of the last great mer de glace the British Islands became continental, and were successively invaded by the Scandinavian and Germanic floras, and the northern and temperate faunas. The climate after a while seems to have become more genial than it is in our day, so that great forests spread far north into regions where trees do not now grow, and reached elevations on the mountains which they cannot now attain. At the same time many southern forms of molluscs migrated into northern seas—some of which have since died out or still survive in diminished numbers and dwarfed in size. To this genial Post-glacial epoch belong the great oaks and other leafy trees in the lower buried forests of the bogs and peat-mosses. Eventually these genial conditions passed away, and the climate of North-west Europe became wet and cold. The British area was insulated, and the land was of less extent than at present—the sea reaching in Scotland to a height of 45-50 feet over the present mean tide-mark. Local or valley-glaciers then made their appearance in many mountain-glens, and even descended in some places to the sea. The formation of the Scottish "carses" or estuarine terraces (45-50 feet terrace) belong to this epoch. Neolithic man lived on the coast and fished in the waters, and his relics occur in the deposits then forming. The climate was not so favourable for the growth of great trees, which were now more restricted in their vertical and horizontal range. Over wide areas the forests decayed and became buried by mosses and other moisture-loving plants in their upward growth. The general occurrence in the peat-bogs of North-western Europe of a second well-marked "buried forest," seems to indicate a bettering of the climate, allowing of a second

period of great forests, which gradually overspread much of the moory and waste land. Coincident with this second forest-epoch there appears to have been a gain of land, at least in Scotland, but

Fig. 397.—PALÆOLITHIC FLINT IMPLEMENT. (R.)

there is no evidence to show that Britain again became joined to the Continent. The second forest-epoch was succeeded as the first had been by somewhat cold wet conditions, under the influence of which the forests decayed and disappeared, and swamps, morasses, and bogs increased; while at the same time the Scottish area became depressed for some 25 feet or so below its present level.

The last physical change of which we have any clear evidence is the retreat of the sea to its present level, while the general aspect of the peat-bogs (in which the rate of waste now exceeds that of growth) would seem to indicate that we are living under drier conditions than obtained when the second forest epoch came to a close.

Correlation of Archæological "Ages" and Geological "Epochs."—Prehistoric relics consist to a large extent of implements, weapons, and ornaments, and these have been classified by archæologists, and arranged according to what is presumed to be their relative antiquity. The ruder kinds of implements, formed of stone, bone, or horn, as they represent a low state of civilisation,

Fig. 398.—ETCHING OF CAVE-BEAR FOUND IN THE CAVE OF MASSAT (ARIÈGE), $\frac{1}{2}$.

are believed to belong to an earlier phase than those which are formed of metals, such as bronze and iron. The use of iron for cutting-implements and weapons, since it argues a greater knowledge of metallurgy, is believed to have succeeded the employment of bronze for such purposes. Geological investigations have strongly supported these inferences, and have shown that for long ages before the knowledge of metals was introduced, Europe was inhabited by races whose only implements and weapons were formed of stone, bone, and horn. These ages are known as the Stone Ages—of which the earlier is called the Palæolithic or Old Stone Age, and the later the Neolithic or New Stone Age. The succeeding epoch, during which bronze gradually replaced stone, is

termed the Bronze Age ; and that, again, passed into the Iron Age, when this last-named metal came into general use for knives and swords. It will be understood, therefore, that these "ages" are merely successive phases of civilisation, and that they overlap each other, some countries having become more rapidly civilised than others. The Palæolithic age was coextensive in Europe with the Pleistocene or Glacial period, while Neolithic man did not appear until after the Arctic flora and fauna had vanished from what are now the temperate regions of Europe. A distinct break, therefore, separates Neolithic from Palæolithic times. Palæolithic man was

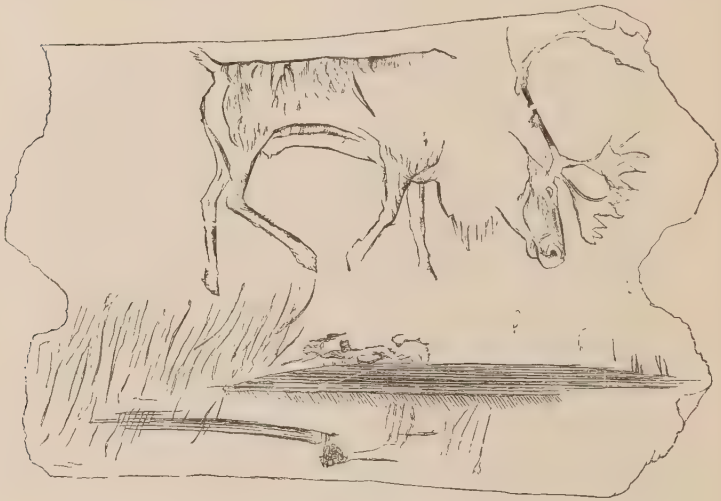


Fig. 399.—REINDEER, ENGRAVED ON ANTLER, $\frac{2}{3}$. FROM THE KESSERLOCH, SCHAFFHAUSEN (HEIM).

associated with many extinct or no longer indigenous mammals; while the fauna of Neolithic times is that of the present day. The last cold phase of the Glacial period separates the Old and New Stone Ages. During that latest cold epoch Palæolithic man hunted the reindeer in the south of France ; after which he seems to have vanished from Europe. At all events we find no trace of him in any Post-glacial accumulations. His Neolithic successor did not appear until the climate had become temperate. Neolithic relics are typically represented by the shell-heaps or "kitchen-middens" of the coast-lands, the buried canoes of the carse-clays, the lake-dwellings of our own and other countries, especially Switzerland and

Italy, and by sepulchral and other remains. While the Palæolithic races (for there were probably more than one) were savages, living by fishing and hunting, having no knowledge of pottery, or agriculture, and possessing apparently no domestic animals, the Neolithic tribes were much further advanced; they fished and hunted, tilled the land, domesticated various animals, and were besides weavers and potters. They had not the artistic gifts, however, of the reindeer hunters of Aquitaine. The Neolithic age can be shown by geological evidence to have commenced long before the advent of any bronze-using people, and similarly it can be proved, from the position of the deposits in which the various relics occur, that bronze continued in use for a long time before the natives of North-western Europe became acquainted with the superior value of iron for tools and weapons.

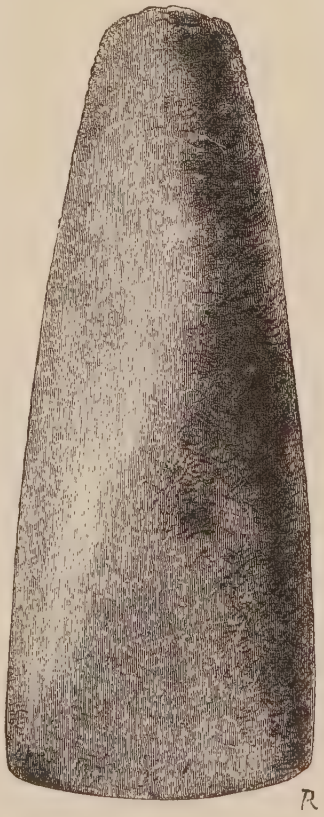


Fig. 400.—NEOLITHIC IMPLEMENT. (R.)

Geographical Conditions of Post-tertiary Times.—Before the advent of the Glacial period Europe had received much of its present configuration—all our mountains had already come into existence, and the great lines of river-drainage were the same then as now. Considerable oscillations of the sea-level, however, took place from time to time during the Pleistocene period. When interglacial conditions prevailed, there would appear to have been direct communication between Southern Europe and North Africa—the Mediterranean being bridged between Sicily and Tunis, and perhaps also between Gibraltar and the opposite coast of Barbary. The British Islands, at the same time, were joined to themselves and the continent,

and the western shores of Europe probably advanced into the Atlantic as far as what is now the 100-fathom line. At another stage of the Pleistocene period, however, very considerable depression ensued, whereby the British area was insulated, and Ireland, Wales, Scotland, and Scandinavia largely submerged. It was probably during late Pleistocene times that the "bridges" across the Mediterranean finally disappeared. In early Post-glacial times Britain again became continental and was probably connected with the Faeröe Islands and Iceland, while Northern Europe extended northwards so as to include Spitzbergen. These conclusions are based on the fact that all those now insulated regions received their floras and faunas from the European mainland in Post-glacial times.

Climate of Post-tertiary Times.—Towards the close of the Pliocene period a general lowering of temperature took place, which at the beginning of Pleistocene times culminated in the development of great snow-fields, ice-sheets, and glaciers, in what are now temperate latitudes. These Arctic or glacial conditions, however, did not continue throughout the Pleistocene period, but were interrupted more than once by prolonged epochs, during which a genial and equable climate prevailed. Moreover, similar but less strongly-marked oscillations of climate were continued into the succeeding Post-glacial and Recent period. There can be no doubt that at the present day the distribution of heat over the globe is largely modified by oceanic currents. The heat of the tropics is thus carried into high latitudes, and diffused by winds and rains over regions which would otherwise have a lower mean annual temperature than they now enjoy. If the warm Gulf Stream ceased to flow into the North Atlantic, there is no reason to doubt that the climate of North-western Europe would become as extreme as that of Labrador. It has been suggested, therefore, that the cold of the glacial climate may have been induced by a great elevation of land in the higher latitudes, by which the Gulf Stream and other warm currents were prevented from flowing into the Arctic seas. But while this would greatly lower the temperature of those high latitudes it could not affect the climate of regions much farther south. The former existence of great glaciers in Central and Southern Europe, in North and South Africa, in Syria and Asia Minor, the great development of the Himalayan glaciers, and the appearances of former extensive glaciation in New Zealand, Australia, South America, Central America, and the high grounds in the southern part of North America, demand some other explanation. Another theory which has met with considerable acceptance has been proposed by Dr James Croll. According to this geologist the

strongly-contrasted climates of the Pleistocene period were brought about by cosmical causes. They were the indirect result of the increased eccentricity of the earth's orbit combined with the precession of the equinox. During a period of high eccentricity the earth, when in aphelion, would be nearly nine millions of miles farther from the sun than it is at present, and when in perihelion it would be over fourteen millions of miles nearer that luminary than it is now. That hemisphere which had its winter in aphelion would then be subject to severe cold, and its snows would not disappear during the succeeding short summer, the temperature of which would be lowered by their presence. Thus in time that hemisphere would be subjected to severe glacial conditions. While such was taking place in the hemisphere whose winter fell in aphelion, the state of things in the other would be greatly different. There the winter would be short and mild, and snow would not accumulate. Under such widely contrasted conditions between the two hemispheres, the trade-winds, and through them the great equatorial currents, would be powerfully affected. The winds blowing from the glaciated hemisphere would be much stronger than those coming from the other, and the equatorial oceanic currents would thus be impelled across the equator into that hemisphere whose summer happened in aphelion. Thus the climate of the latter would be rendered extremely temperate. The winter would be short and mild, and the summer long and genial—there would be no great difference, in short, between the seasons. But while the influx of warm water would increase the temperature of the one hemisphere, the absence of any warm tropical ocean currents would greatly intensify the cold in the opposite hemisphere. Thus, while the latter was being subjected to all the rigours of a Glacial period, the former would be enjoying a kind of perennial summer. Owing to the precession of the equinox, however, the conditions of the two hemispheres would be reversed every 11,000 years or so—the snows would gradually disappear from the one, while the climate of the other continued to deteriorate, until everything became changed. In this way great migrations of plants and animals would take place from time to time. According to this theory, therefore, the cold phases of the Pleistocene period took place at a time when our hemisphere had its winter in aphelion; while the mild interglacial epochs of the same period gradually supervened when, owing to the precession of the equinoxes, our seasons were reversed, and winter happened in perihelion. And as the last great period of eccentricity commenced some 240,000 years ago, this would give us a date for the beginning of Pleistocene time, and the advent in Europe of Palæolithic man. As the eccen-

tricity diminished, the recurrent oscillations of climate, according to this hypothesis, would become less marked; and this we find to have been actually the case—the alternations of climate in the Post-glacial and Recent period not presenting nearly such vivid contrasts as those of Pleistocene times.

It has been objected to Dr. Croll's theory that we do not meet with any evidence in the deposits of older geological periods of such remarkable oscillations of climate, which, if his theory be true, ought to have happened again and again during preceding periods of high eccentricity of the orbit. To this it has been replied that we do meet with the only kind of evidence that we could expect to find in aqueous rocks, most of which are old marine sediments. Erratics have been encountered in many formations, even as far back as Palæozoic times, and now and again, as in the Old Red Sandstone and the Permian, we encounter accumulations which can hardly have had any other than a glacial origin. Again, we must remember that before we can have a well-marked glacial period, we must have a broad land-surface on which snows can accumulate and ice-fields form. During the deposition of the Mesozoic and Palæozoic formations the European and American continents were much less extensive than they are now; and although wide land-areas existed even as far back as Cambrian times, yet these were not so continuous as they became in later periods of the world's history. It is extremely doubtful whether the distribution of land and water in our hemisphere at any period anterior to the later Cainozoic era could have favoured such enormous accumulations of snow and ice as those of the Pleistocene. Glacial conditions may have supervened again and again without leaving any conspicuous evidence behind them. Suppose, for example, that a severe climate took place during some stage of the Silurian era, what kind of evidence of such cold conditions might we now expect to meet? Where are the lands with their roches moutonnées and boulder-clays? No old land-surface of that period has been preserved. But if glaciers descended to the sea and coast-ice formed, then erratics might have been distributed over the bed of the sea and become entombed in sediment; and such erratics, as we have seen, do occur in the Silurian strata of some regions. But if severe climatic conditions really did obtain at the period in question, would not they have affected the flora and fauna, causing great migrations, and bringing about the modification and extinction of species? This might have happened without our being able now to detect any evidence of such changes. We know practically nothing of the terrestrial life of the globe at that far-distant time, and the marine organisms of the period could suffer comparatively

little; they would simply migrate into more genial waters, and return to their former habitats when the unfavourable conditions had passed away.

Although the geological evidence is upon the whole best explained by Croll's theory, yet there are certain phenomena which the latter seems hardly to account for. Recent observations, for example, have shown that even amongst the mountains of tropical regions considerable snowfields and glaciers have formerly existed. This would appear to indicate that the cold climatic conditions of Pleistocene times were the result of a general lowering of the temperature of the whole globe—the glacial epochs of northern and southern hemispheres having been contemporaneous and not alternating as Croll has inferred.

APPENDIX A.

TABLE OF BRITISH FOSSILIFEROUS STRATA.

QUATERNARY or POST-TERTIARY.	Recent and Post-glacial (Neolithic, etc.)			Raised Beaches and Estuarine Flats; Lacustrine and Fluviatile Deposits; Bogs or Peat-Mosses; Moraines and Fluvio-glacial Gravels, etc.
	Pleistocene or Glacial (Palæolithic)			Late Glacial Deposits; Interglacial Deposits; Glacial and Fluvio-glacial Deposits.
CAINOZOIC or TERTIARY.	Pliocene	Newer		Cromer Forest-bed Group. Chillesford and Weybourn Crags. Norwich Crag.
		Older		Red Crag and St. Erth Beds. Coralline Crag and Lenham Beds.
	Miocene			(Wanting in Britain.)
	Oligocene			Hamstead Beds. Bembridge Beds. Osborne or St. Helen's Beds. Headon Beds. Bovey Tracey Beds and Leaf-beds of Mull, Skye, and Antrim.
	Eocene	Upper		Headon Hill Sands; Barton Clay; Upper Bagshot Sands.
		Middle		Bracklesham Beds and Middle Bagshot Sands.
		Lower		Lower Bagshot Sands. London Clay and Bognor Beds. Oldhaven Beds. Woolwich and Reading Series. Thanet Sands.
MESOZOIC or SECONDARY.	Cretaceous	Upper		Upper Chalk. Middle Chalk. Lower Chalk and Chalk Marl. Upper Greensand. Gault.
		Lower (Neocomian)		Lower Greensand. Weald Clay. Hastings Sand.

- MESOZOIC or SECONDARY.
  - Jurassic.
    - Upper or Portland Oolites.
      - Purbeck Beds.
      - Portland Beds.
      - Kimeridge Clay.
    - Middle or Oxford Oolites
      - Coral Rag.
      - Oxford Clay.
    - Lower or Bath Oolites.
      - Cornbrash and Forest Marble.
      - Great or Bath Oolite, with Stonesfield Slate.
      - Fuller's Earth.
      - Inferior Oolite.
    - Lias.
      - Upper Lias.
      - Marlstone.
      - Lower Lias.
  - Triassic.
    - Rhætic.
      - Penarth Beds.
    - Upper or Keuper.
      - New Red Marl.
      - Lower Keuper Sandstone.
    - Middle.
      - (Wanting in Britain.)
    - Lower or Bunter
      - Upper Mottled Sandstone.
      - Pebble Beds.
      - Lower Mottled Sandstone.
- PALÆOZOIC or PRIMARY.
  - Permian.
    - Upper.
      - Red Sandstones, Clays, etc.
      - Magnesian Limestone.
      - Marl Slate.
    - Lower.
      - Red Sandstones, Clays, Breccias, and Conglomerates.
  - Carboniferous
    - Coal-Measures.
      - Red Sandstones, and Upper Coal-bearing Series.
      - Middle Coal-bearing Series.
      - Lower Coal-bearing Series ("Ganister Beds").
    - Millstone Grit.
      - Thick Sandstones, etc.
    - Carboniferous Limestone.
      - Yoredale Beds.
      - Main or Scaur Limestone.
      - Lower Limestone Shale (England), and Calciferous Sandstones (Scotland).
  - Devonian and Old Red Sandstone
    - Upper Devonian
    - Middle ,,
    - Lower ,,

    (Upper and Lower Old Red Sandstone.)
  - Silurian.
    - Upper.
      - Ludlow Group.
      - Wenlock Group.
      - Upper Llandovery Group.
    - Lower.
      - Lower Llandovery Group.
      - Bala and Caradoc Group.
      - Llandeilo Group.
      - Arenig or Stiper Stone Group.
  - Cambrian or Primordial
    - Upper.
      - Tremadoc Slates.
      - Lingula Flags.
    - Middle.
      - Menevian Group.
    - Lower.
      - Harlech and Llanberis Group.
  - Archæan or Pre-Cambrian.
    - Torridon Sandstones, etc.;
    - Lewisian or Hebridean Gneiss.

APPENDIX B.

THE ANIMAL KINGDOM.

Invertebrate Animals.

I.—PROTOZOA.

1 Rhizopoda (more or less amœboid units): including especially the calcareous *Foraminifera* (entering largely into the composition of many limestones), and the mainly flinty-shelled *Radiolaria* (forming siliceous deposits).
2. Infusoria (actively motile forms): no fossil forms, unless some mailed *Dinoflagellata* in the Chalk.
3. Gregarinida (passive parasites): no fossil forms.

II.—PORIFERA or SPONGIDA.

1. Calcispongiæ: limy "skeleton;" many fossil forms.
2. Silicispongiæ: flinty spicules (*Hexactinellida, Lithistida, Tetractinellida, Monaxonia*); many fossil forms.
3. Ceratospongiæ: horny fibres; doubtfully fossil.
   [The Myxospongiæ (without spicules) are probably degenerate forms from different sources.]

III.—CŒLENTERATA.

A. HYDROZOA.

1. Hydromedusæ: comprising the fresh-water Polypes (*Hydridæ*), which have no fossil representative; the Pipe-corallines (*Tubulariдæ*) with a few fossils; the zoophytes (Gymnoblastic and Calyptoblastic hydroids), some of which (*e.g.* Sertularida) include fossils; also medusoid types, either connected with zoophytes, or entirely apart from such (Trachymedusæ); also *Hydrocorallinæ* (Millepores and Stylasterids), both recent and extinct, formerly grouped as "Tabulate corals."
2. Siphonophora: Oceanic, *e.g.* the Portuguese-man-of-war (Physalia); no fossils, unless the abundant and entirely extinct Graptolites (*Graptolitidæ*) be placed about here.
3. Acraspeda: marine jelly-fishes; very rarely found fossil (Solenhofen Slates); impressions in Swedish Cambrian and Silurian. The aberrant *Lucernarida* may be included here.
4. Ctenophora: free-swimming divergent forms, often ranked as a separate division; no fossils.

B. ACTINOZOA.

1. Zoantharia (*Hexacoralla*): including *Actiniaria* (without skeleton), no fossils; *Antipatharia* (horny), "Black corals," only one fossil

representative of late Tertiary age; *Madreporaria* (limy), reef-corals, star-corals, Fungidæ, etc., abundant as fossils.

2. Alcyonaria (*Octocoralla*): including *Alcyonidæ* (Deadmen's-fingers, Alcyonium), no fossils; *Helioporidæ*, a number of fossil forms Heliolites), one extant (Heliopora); *Tubiporidæ* (Organ-pipe corals), a few fossils, some of which were formerly called "Tabulate;" *Gorgonidæ* (Gorgonia, Red Coral, etc.), sparingly fossil; *Pennatulidæ* (Pennatula, Sea-pen, etc.), a few fossil forms.
3. Rugosa (*Tetracoralla*): includes a vast number of fossil forms, chiefly Palæozoic; the group is now all but extinct (2 genera).

IV.—VERMES.

A heterogeneous provisional division without unity.

1. Platyelmia: Turbellaria, Trematoda (Flukes), Cestoda (Tapeworms), Nemertida.
2. Nematelmia: Nematoda (Thread-worms), Acanthocephala.
3. Echiuroidea, Gephyrea, Chætognatha, Rotifera, and small groups. No fossil traces of these and preceding groups 1 and 2, except some thread-worms in amber and hints of Gephyrea.
4. Discophora: Hirudinea (Leeches); only very doubtful fossil traces.
5. Chætopoda: including *Oligochæta* (common Earthworm), possibly represented by some of the worm-burrows met with more or less abundantly in many formations; *Polychæta* (Sand-worms), the horny jaws of free-living forms occasionally occur as fossils, but they are chiefly represented by burrows, tracks or trails, and castings; the tube-inhabiting forms (Tubicola) are common as fossils, *e.g. Serpulidæ*.
6. Polyzoa or Bryozoa (Lace-corals, Sea-mats, etc.); aberrant colonial forms, common as fossils.
7. Brachiopoda (Lamp shells): aberrant bivalved forms; abundant as fossils.
   - *a. Inarticulata*, valves not hinged, *e.g.* Crania, Discina, Lingula.
   - *b. Articulata*, valves hinged, *e.g.* Terebratula, Rhynchonella.

[*Note.*—Polyzoa and Brachiopoda are frequently included under a separate division as MOLLUSCOIDA.]

V.—ECHINODERMATA.

1. Holothuroidea (Sea-cucumbers): certain calcareous spicules (Carboniferous) have been referred to this order.
2. Echinoidea (Sea-urchins): many fossil forms.
3. Asteroidea (Star-fish): fossil forms not uncommon.
4. Ophiuroidea (Brittle Stars): some fossil forms.
5. Cystoidea (extinct).
6. Blastoidea (extinct).
7. Crinoidea (Sea-lilies): many fossil forms.

VI.—ARTHROPODA.

1. Crustacea: the following orders are represented by fossil forms:—*Phyllopoda* (Brine-shrimps, etc.); *Ostracoda* (Water-fleas); *Cirripedia* (Barnacles and Acorn-shells); *Amphipoda* (Sand-hoppers); *Isopoda* (Wood-lice, etc.); *Stomatopoda* (Locust, Shrimps, etc.); and

Decapoda, viz. Macrura (Lobsters, Shrimps, Hermit-crabs); and Brachyura (Crabs). Usually included by geologists under CRUSTACEA are the extinct orders *Trilobita* and *Eurypterida*, which have affinities with the *Xiphosura* (King-crabs), and with smaller divisions between crustaceans and arachnids, and ought therefore to be ranged under ARACHNIDA.

2. PROTOTRACHEATA (primitive insect type): Peripatus; no fossil form.
3. MYRIAPODA: the fossil forms are referred chiefly to the orders of *Chilopoda* (Centipedes) and *Chilognatha* (Millepedes, Galley-worms, etc.)
4. ARACHNIDA: including the modern Spiders and Scorpions, and *Pœcilopoda* or *Xiphosura* (King-crabs, Limulus), with a few fossil forms.
5. INSECTA: most of the existing orders are represented by fossils, especially *Orthoptera* (Locusts, Grasshoppers, Cockroaches); *Hemiptera* (Bugs, Water-bugs, etc.); *Diptera* (Gnats, House-flies, etc.); *Neuroptera* (Ant-lion, Caddis-fly); *Lepidoptera* (Butterflies and Moths); *Hymenoptera* (Ants, Bees, Wasps); *Coleoptera* (Beetles).

VII.—MOLLUSCA.

1. ISOPLEURA: Primitive forms, *e.g.* Chiton; numerous fossil forms.
2. LAMELLIBRANCHIATA (Bivalves): *e.g.* Cockle, Mussel, Scallop; common as fossils.
3. SCAPHOPODA: Elephant's-tooth shells, Dentalium; numerous fossil species.
4. GASTEROPODA (Univalves):
    1. Prosobranchiata: including *Siphonostomata* (aperture of shell is notched or produced into a canal; marine and mostly carnivorous) and *Holostomata* (aperture of shell is entire; marine and fresh-water, mostly live on plants); abundant fossils.
    2. Heteropoda (Pelagic molluscs): few fossil forms.
    3. Opisthobranchiata (Sea-slugs, etc.): including *Tectibranchiata* and *Nudibranchiata*; of the former numerous fossils.
    4. Pulmonata (respiration aerial): including the snails and slugs; of the former abundant fossil representatives.
5. PTEROPODA (Pelagic swimming molluscs): not uncommon as fossils.
6. CEPHALOPODA (Marine Carnivorous molluscs):
    a. *Tetrabranchiata* (Nautilus, etc.); many fossil forms.
    b. *Dibranchiata* (Cuttle-fishes, etc.); many fossil forms.

Vertebrate Animals.

VIII.—TUNICATA.

UROCHORDA (degenerate primitive vertebrates). In certain of the modern Ascidians or Sea-squirts calcareous spicules occur; it is possible therefore that some fossil spicula which have been referred to other forms may really represent the Tunicata. Recently an ascidian has been recorded from beds of Pliocene age.

Note.—Approaching Tunicata, and out of the Invertebrate ranks, there should probably be placed two aberrant genera (*Hemichordata*), Balanoglossus and Cephalodiscus, both with incipient vertebrate characteristics.

IX.—CEPHALOCHORDA.

PHARYNGOBRANCHII (Lancelet, or Amphioxus): no fossil form.

X.—CYCLOSTOMATA.

MARSIPOBRANCHII (Hag-fish and Lamprey): no fossils, unless the doubtful tooth-like objects called "Conodonts" be such.

XI.—PISCES (Fishes).

1. PALÆICHTHYES:
   - *a.* Elasmobranchii or Selachii (Sharks and Rays): many fossil forms.
   - *b.* Holocephali, or Chimæroidei (Chimæra or "King of the Herrings"); some fossil forms.
   - *c.* Ganoidei (Armoured Fishes, such as Bony Pike, Sturgeon, and many fossil forms).
   - *d.* Dipnoi (Mud-fishes): a few fossil forms.
2. TELEOSTEI (Bony Fishes, such as Salmon, Cod, Perch, etc.): many fossil forms.

XII.—AMPHIBIA.

1. LABYRINTHODONTIA or STEGOCEPHALA (extinct): many forms.
2. GYMNOPHIONA (Apoda): Cæcilia; no certain fossil forms.
3. URODELA (Tailed Amphibians, such as Newts, Salamanders, etc.): not common as fossils.
4. ANURA (Tailless Amphibians, such as Frogs and Toads): not common as fossils.

XIII.—REPTILIA.

1. ICHTHYOSAURIA (extinct): *e.g.* Ichthyosaurus.
2. PLESIOSAURIA (extinct): *e.g.* Plesiosaurus, Nothosaurus.
3. DICYNODONTIA or ANOMODONTIA (extinct): in part related to the next, *e.g.* Dicynodon, Oudenodon (*Cryptodont*). Here also may be inserted the *Theriodonts* (Galesaurus), with carnivorous-like dentition.
4. CHELONIA (Turtles and Tortoises): occur as fossils.
5. PTEROSAURIA (extinct): Flying Saurians, *e.g.* Pterodactyl.
6. LACERTILIA (Lizards, etc.): occur as fossils.
7. OPHIDIA (Snakes): occur as fossils, but not numerous.
8. CROCODILIA (Alligators and Crocodiles): occur as fossils.
9. ORNITHOSCELIDA (extinct): nearest Birds; including *Dinosauria* (Iguanodon, Megalosaurus) and *Compsognatha* (Compsognathus).

XIV.—AVES (Birds).

1. SAURURÆ (extinct): with marked Saurian affinities; represented by *Archæopteryx*.
2. ODONTORNITHES (extinct): Toothed Birds, a heterogeneous group, *e.g.* Hesperornis, Ichthyornis.
3. RATITÆ (the Cursorial Birds, with unkeeled breast-bone, such as Emeu and Ostrich): fossil forms occur in Tertiary deposits.
4. CARINATÆ (Birds with a keeled breast-bone, and mostly with the power of flight), embracing the popular orders of *Natatores* (Swimmers), *Grallatores* (Waders), *Rasores* (Scratchers), *Scansores* (Climbers), *Insessores* (Perchers), *Raptores* (Birds of Prey). All these have fossil representatives.

XV.—MAMMALIA.

A. Prototheria, Ornithodelphia, Monotremata (oviparous): Duck-mole, and Echidna; of the latter fossil upper arms.
B. Metatheria, Didelphia, Marsupialia (no placenta): Kangaroos, Opossums, etc.; numerous fossils.
C. Eutheria, Monodelphia, Placentalia (with placenta):
  a. Edentata (Sloths, etc.); fossil forms not numerous, *e.g.* Glyptodons.
  b. Sirenia (Dugong, Manatee); fossil forms not very numerous.
  c. Cetacea (Whale, Dolphin, etc.); numerous fossil forms, *e.g.* Zeuglodons.
  d. Rodentia (Hare, Rat, Beaver, Squirrel, etc.); numerous fossil forms.
  e. Hyracoidea (Conies); no fossil form.
  f. Proboscidea (Elephant); numerous fossil species, *e.g.* Mastodon and Dinotherium. Here include the extinct *Amblypoda* (Coryphodon and Dinoceras), and the *Condylarthra* (Phenacodus), primitive hoofed animals.
  g. Ungulata:
    a. Perissodactyla (Horse, Rhinoceros, etc.); numerous fossils (Palæotherium, etc.).
    b. Artiodactyla (Ox, Deer, Hippopotamus, etc.).
  h. Insectivora (Moles, Hedgehog, etc.); numerous fossil forms.
  i. Cheiroptera (Bats); fossil forms rare.
  k. Carnivora (Cat, Dog, Bear, Seal, Walrus, etc.); numerous fossil forms.
  l. Prosimiæ (Lemurs); fossil forms.
  m. Primates:
    (*a*) Arctopithecini (Marmosets); no fossil forms.
    (*b*) Platyrrhini (New World Monkeys); fossil forms.
    (*c*) Catarrhini (Old World Monkeys); fossil forms.
    (*d*) Anthropidæ (Man).

[For the preceding classification of Animals I am indebted to my friend Mr. J. Arthur Thomson.]

APPENDIX C.

THE VEGETABLE KINGDOM.

Cryptogams or Flowerless Plants:—

THALLOPHYTES (Fungi, Algæ).
BRYOPHYTES (Liverworts, Mosses).
PTERYDOPHYTES (Ferns, Horse-tails, Club-mosses).

Phanerogams or Flowering Plants:—

GYMNOSPERMS (Pines, Cycads).
MONOCOTYLEDONS or ENDOGENS (Grasses, Lilies, Palms).
DICOTYLEDONS or EXOGENS (ordinary Leafy Trees, Shrubs, and Flowering Plants).

GLOSSARY.

Abrasion (L. *ab*, from; *rasus*, rubbed or scraped): the operation of wearing away by aqueous or glacial action.

Accretion (L. *accretio*, an increase): increase by external addition of new matter.

Acicular (L. *acicula*, a little needle): applied to minerals occurring in needle-like crystals.

Acrogens (Gr. *akros*, high; *gennao*, I produce): plants which increase by growth at the summit or growing point.

Alkalies (Ar. *alqali*, the salt of ashes): compound substances, very soluble in water, which turn litmus blue and turmeric brown. The principal mineral alkalies are potash, soda, lithia, and ammonia.

Alkaline earths: hydrates of baryta, strontia, lime, and magnesia, the first three of which exhibit a strong alkaline reaction; the hydrate of magnesia is only feebly alkaline.

Amorphous (Gr. *a*, without; *morphe*, form): without regular or determinate structure.

Amphibia (Gr. *amphi*, both; *bios*, life): animals which have gills when young, but can breathe air directly when adult.

Amygdaloidal (Gr. *amugdalon*, an almond; *eidos*, an appearance): applied to igneous rocks containing vesicular cavities which are often filled or partially filled with subsequently-introduced mineral matter. The cavities are frequently almond-shaped: the mineral kernels are called *amygdules*.

Angiosperms (Gr. *angeion*, a vessel; *sperma*, seed): plants which have their seeds enclosed in a seed vessel.

Annulosa (L. *annulus*, a ring): animals whose bodies are more or less distinctly composed of a succession of rings.

Anticlinal (Gr. *anti*, against; *klino*, I bend): applied to strata which are inclined in opposite directions from a common axis, *i.e.* in a roof-like form. Strata so arranged form what is called an *anticline* or *saddle-back*.

Arenaceous (L. *arena*, sand): sandy; composed of grains of sand.

Argillaceous (L. *argilla*, white clay): applied to rocks composed of clay, or in which a notable quantity of clay is present.

Arkose (Eng. *ark*): a rock composed of the materials of disintegrated granite; granitic sandstone.

Articulata (L. *articulus*, a little joint): animals which have jointed bodies or jointed limbs: such as insects, centipedes, spiders, and crustaceans.

Azoic (Gr. *a*, without; *zoe*, life): applied to rocks which contain no fossils.

Backs: a miner's term for strike-joints; *cutters* is the mining term for *dip-joints*. *Back* is also a miner's term for the outcrop of a lode.

Basin (Fr. *bassin*): applied to strata dipping towards a common centre or axis; also to hollows occupied by lakes and seas.

Basset, Basset-edge (Sp. *bisel*, bevel-edge of a thing): a miner's term for *outcrop*.

Botryoidal (Gr. *botrus*, a bunch of grapes; *eidos*, shape): applied to minerals or rocks which occur in masses having the form of clusters of grapes.

Brachiopods (Gr. *brachion*, the arm; *podes*, feet): molluscoids which have two fleshy spiral arms developed from the sides of the mouth: bivalve, one shell being on the back and another in front.

Cainozoic (Gr. *kainos*, recent; *zoe*, life): applied to the younger systems of stratified rocks = *Tertiary*.

Calciferous (L. *calx*, lime; *fero*, I bear): applied to strata which contain beds of cornstone or limestone; or in which calcareous matter is more or less plentifully diffused.

Cephalopods (Gr. *kephale*, the head; *podes*, feet): molluscs which have the principal organs of locomotion arranged round the head.

Cestracionts (Gr. *kestra*, a pike, a weapon): a sub-family of sharks, provided with strong fin-spines and plate-like crushing teeth: represented at present by only one form—the Port Jackson shark.

Chalybeate (L. *chalybs*, very hard iron): applied to water impregnated with iron oxide.

Clastic (Gr. *klastos*, broken): applied to rocks composed of fragmental materials.

Cleavage (A.S. *clúfan*, to split or cleave): that structure in minerals which allows of their being split most readily along certain definite planes. *Slaty cleavage:* a structure in certain rocks, as clay-slate, which renders them capable of being cleaved or split into slabs, plates, or laminæ, in a direction independent of the planes of sedimentation.

Clinkers (Dut. *klinker*, that which sounds): the cindery-like masses forming the crust of some lava-flows.

Concretion (L. *concretus*, grown together): a mass formed by irregular aggregation or accretion of mineral matter, very often round a nucleus; not to be confounded with crystallisation. *Concretionary*, applied to rocks formed of or containing concretions.

Conformable: applied to strata lying one above another in parallel sequence. *Conformity:* a conformable sequence between groups of strata; an unbroken succession of strata.

Coulée (F.): a stream of lava whether flowing or become solid.

Crust of the Earth: those outer portions of the earth which are accessible to geological investigation.

Débâcle (F., breaking of a frozen river): a tumultuous rush of water, sweeping forward rock-débris, etc.

Degradation (F. *dégrade*): the wasting or wearing down of the land under the influence of the epigene forces.

Dendritic (Gr. *dendron*, a tree): applied to certain inorganic plant-like markings which occur on the faces of fissures and joints in rocks.

Denudation (L. *denudare*, to make naked): the laying bare of underlying strata by the removal of superficial matter; the process by which the earth's surface is broken up and the loose material carried away.

Derivative rocks: another name for *Clastic* rocks: rocks which have been derived from or formed out of the materials of pre-existing rocks.

Detritus (L., worn): any accumulation of materials formed by the breaking-up and wearing-away of rocks.

Diatoms (Gr. *diatome*, dissection): microscopic plants, provided with siliceous envelopes; an order or tribe of the Algæ.

Dibranchiate (Gr. *dis*, twice; *brangchia*, gills): applied to the cephalopods which possess only two gills.

Dicotyledons (Gr. *dis*, twice; *kotuledon*, a cup-like hollow): plants whose seeds consist of two lobes.

Dyas (Gr. *duas*, two): another name for the Permian system: from the rocks consisting (in Germany, etc.) of two great divisions.

Echinoderms (Gr. *echinos*, a hedgehog; *derma*, skin): a class of animals most of which have spiny skins, such as sea-urchins.

Endogens (Gr. *endon*, within; *gennao*, I produce): plants whose growth takes place from within; such as palms, rushes, grasses, etc.

Endomorph (Gr. *endon*, within; *morphe*, form): a mineral enclosed within another mineral.

Epigene (Gr. *epi*, upon; *gennao*, I produce): applied to the geological agents which act upon the surface of the earth.

Erosion (L. *erosus*, consumed or gnawed away): the work of wearing away done by rivers, the sea, and glacier-ice.

Eskers: name given in Ireland to ridges and mounds of gravel and sand of glacial age: same as *kames* (Scotland) and *åsar* (Sweden).

Exogens (Gr. *exo*, without; *gennao*, I produce): plants which grow by additions to the outside of the wood, in the form of annual concentric layers (the ordinary leafy trees).

Exuviæ (L., cast-off clothes): external parts or coverings of crustaceans, molluscs, etc.

Ferruginous (L. *ferrum*, iron): containing a notable amount of oxide of iron.

Fluvio-marine (L. *fluvius*, a river; *mare*, the sea): applied to deposits which are partly of fluviatile, partly of marine origin.

Foraminifera (L. *foramen*, an aperture; *fero*, I bear): minute organisms with complicated shells, which are often perforated for the passage of processes of the body-substance.

Formation: a series of rocks having some character in common, whether of origin, age, or composition; often applied to a group of strata containing a well-marked and distinctive assemblage of fossils—a group of subordinate importance to a *system*.

Fracture (L. *fractus*, broken in pieces): the fresh surface of a rock produced by the blow of a hammer. When the fracture is plane it is said to be *even;* when convex and concave or shell-like, it is *conchoidal;* when the rock breaks into thin irregular wedge-shaped splinters, the fracture is *splintery*. Other descriptive terms are *shattery*, *flinty*, *shaly*, *friable*, *earthy*, etc.

Fragmental rocks, see **Clastic** and **Derivative**.

Fumaroles (It. *fumare*, to smoke): the steam and gases which escape from the crevices and cracks, etc., of a lava-flow.

Gangue (Ger. *gang*, a walk or gallery): the matrix or vein-stuff in which an ore or other mineral is embedded.

Ganister: a miner's term for hard siliceous grits which occur at the base of the Coal-measures in England.

Gasteropods (Gr. *gaster*, the belly; *podes*, feet): univalve molluscs, provided with a ventral muscular disk, adapted for creeping.

Gymnosperms (Gr. *gumnos*, naked; *sperma*, seed): plants in which the seed is not encased in a seed-vessel (the conifers and cycads).

Hade: a miner's term for the inclination or deviation of a lode or fault from the vertical.

Heave: a miner's term for the horizontal displacement of an outcrop by a fault.

Heterocercal (Gr. *heteros*, diverse; *kerkos*, a tail): applied to fishes having unequally lobed tails.

Heteropods (Gr. *heteros*, diverse; *podes*, feet): a group of the gasteropods in which the foot acts as a swimming organ.

Homocercal: (Gr. *homos*, alike; *kerkos*, a tail): applied to fishes having equally bilobate tails.

Horizon: a bed or series of beds in a larger group marked by the presence of a particular fossil or fossils, or characterised by some distinctive feature: a geological datum line.

Hybodont (Gr. *hubos*, curved or humped; *odous*, a tooth): a group of the cestracionts, provided with fin-spines and shark-like teeth, which are not so trenchant, however, as those of the true sharks.

Hydrates (Gr. *hudor*, water): minerals containing water in a state of chemical combination.

Hydrothermal (Gr. *hudor*, water; *therme*, heat): applied to the action of heated waters within the crust of the globe.

Hypogene (Gr. *hupo*, under; *gennao*, I produce): applied to geological action within the earth.

Igneous (L. *igneus*, burning): applied to the action and operation of subterranean heat; also to rocks which have been erupted from the heated interior of the earth.

Infusoria: minute animal organisms inhabiting water containing decaying organic matter: so called from their being obtained (for investigation) in infusions of vegetable matter exposed to the air. The so-called *infusorial earths* are composed principally of diatoms and not infusoria.

In situ (L., in place): applied to minerals, fossils, and rocks which occupy their natural place or position.

Intrusive: applied to igneous rocks which have been injected among pre-existing rocks = *Subsequent*, *i.e.* of later date than the rocks amongst which they occur.

Isoclinal (Gr. *isos*, equal; *klino*, I bend or incline): applied to a series of highly folded strata which are all inclined in one direction.

Lamellar (L. *lamella*, a small plate of metal): composed of leaves or thin plates.

Lamellibranchs (L. *lamella*, a small plate of metal; Gr. *brangchia*, gills): bivalve molluscs, having gills in symmetrical layers.

Lithoidal (Gr. *lithos*, a stone; *eidos*, resemblance): having a stony texture or appearance.

Lithology (Gr. *lithos*, a stone; *logos*, a discourse): the science or study of rocks as mineral substances = *Petrology*.

Mesozoic (Gr. *mesos*, middle; *zoe*, life): the great division of sedimentary formations containing the middle forms of life; the era coming between the Palæozoic and the Cainozoic.

Metamorphic (Gr. *meta*, beyond; *morphe*, form): applied to rocks which have been more or less completely changed from their original condition.

Moffette (Ital.): emanations of carbonic acid gas; common in many regions of dormant volcanic action.

Monoclinal (Gr. *monos*, alone; *klino*, I bend): applied to a single fold in gently-inclined or horizontal strata when there is an abrupt increase of dip followed by an abrupt resumption of horizontality.

Monocotyledons (Gr. *monos*, alone; *kotuledon*, a cup-shaped hollow): plants which have only one seed-lobe.

Neozoic (Gr. *neos*, new; *zoe*, life): a term which includes the Secondary, Tertiary, and Quaternary systems.

Open-cast: a miner's term for the method of working a vein or bed at the outcrop, open to the day.

Palæozoic (Gr. *palaios*, ancient; *zoe*, life): the first great division which includes the oldest of the sedimentary formations—those which contain the most ancient relics of life.

Pelagic (Gr. *pelagos*, the sea): applied to accumulations forming at abysmal depths of the ocean.

Perimorph (Gr. *peri*, round about, *morphe*, form): a mineral enclosing another mineral or minerals.

Petrology (Gr. *petros*, a rock; *logos*, a discourse): the science or study of rocks considered as mineral substances.

Placoid (Gr. *plax*, a plate; *eidos*, resemblance): applied to an order of fishes (sharks and rays) the skins of which are covered irregularly with bony plates, tubercles, and spines.

Plutonic (Pluto, the god of the infernal regions): applied to deep-seated igneous action; also to deep-seated igneous rocks—those which have not been erupted at the surface.

Protozoa (Gr. *protos*, first; *zoon*, an animal): the lowest division of the animal kingdom.

Psammites (Gr. *psammos*, sand): rocks formed of sand and gravel.

Pseudomorph (Gr. *pseudos*, false; *morphe*, form): a mineral which has replaced another and assumed its crystalline form.

Pteropods (Gr. *pteron*, a wing; *podes*, feet): molluscs that swim by means of two lateral appendages attached near the head.

Puy (Fr.): a provincial term for the conical volcanic hills of Auvergne; applied generally to any small volcanic cone.

Quaquaversal (L. *quaqua*, on every side; *versus*, turned): applied to strata that dip in all directions from a common centre; dome-shaped strata.

Quincunx (L. *quinque*, five; *uncia*, a twelfth part): applied to the mode in which the leaf-scars of certain trees are arranged; these are so disposed in lines that the members of each succeeding line stand immediately behind those in the preceding one.

Schists (Gr. *schistos*, divisible): rocks which have a superinduced foliated structure.

Solfatara (It. *solfo*, sulphur): a volcanic vent or fissure, from which only vapours and gases are discharged.

Spore (Gr. *spora*, seed): the reproductive germ of cryptogamic plants, as ferns and club-mosses.

Synclinal (Gr. *sun*, together; *klino*, I bend): applied to strata that dip from opposite directions inwards to one common axis. *Syncline*: a basin-shaped or trough-like arrangement of strata.

Tabular (L. *tabula*, a board or plank): applied to minerals occurring in table-like forms; also to rocks which are arranged in table-like masses.

Tabulata: corals with horizontal plates, or *tabulæ*, extending across the body-cavity.

Testaceous (L. *testa*, shell), applied to animals provided with a shell or hard covering.

Tetrabranchiate (Gr. *tetra*, four; *brangchia*, gills): applied to the cephalopods which possess four gills.

Tilted up: applied to strata that are abruptly turned up at a high angle of inclination.

Urodele (Gr. *oura*, tail; *delos*, visible): applied to the tailed amphibians.

Zoophyte (Gr. *zoön*, animal; *phuton*, a plant): plant-like animals, such as Alcyonarians, Graptolites, Crinoids, etc.

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